Vector Meson Photoproduction in UPCs at RHIC

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CFNS (virtual) Workshop:
Photon-Induced Interactions
April 26-28, 2021

- Ultra-Peripheral Collisions (UPC) & VM, STAR detector & UPC data selection

RHIC versatility:

- Au+Au: UPC J/ψ & ρ
- d+Au: UPC J/ψ
- polarized p$\uparrow$+Au: UPC J/ψ

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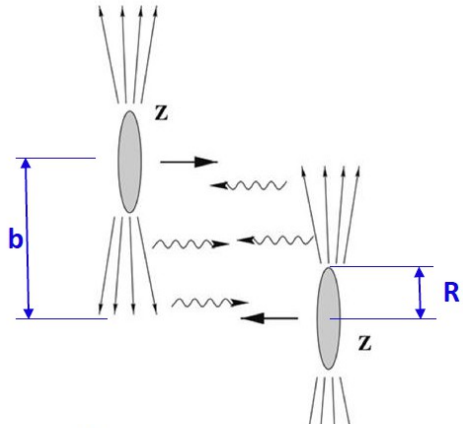
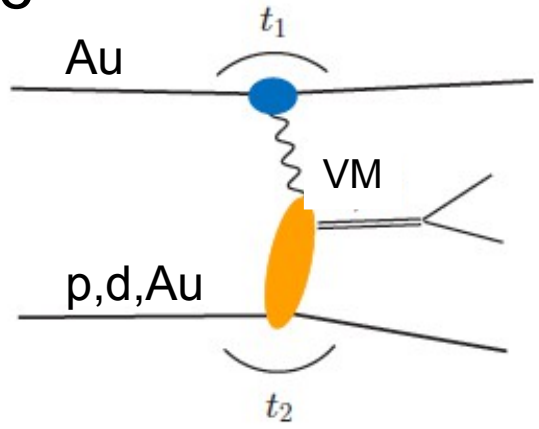
Ultra-Peripheral Collisions (UPC)

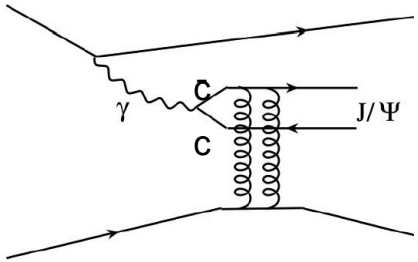
- UPC: b > 2R, hadronic interactions suppressed
- Large flux of photons coming from Weizsaecker-Williams:



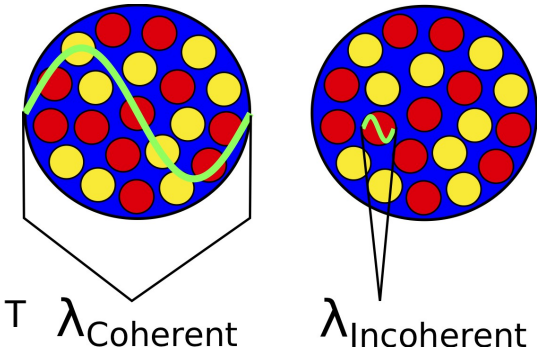
- WW photon from one (high Z Au) beam particle → photoproduction on other beam particle:



- e.g. J/ψ production, sensitive to gluons:



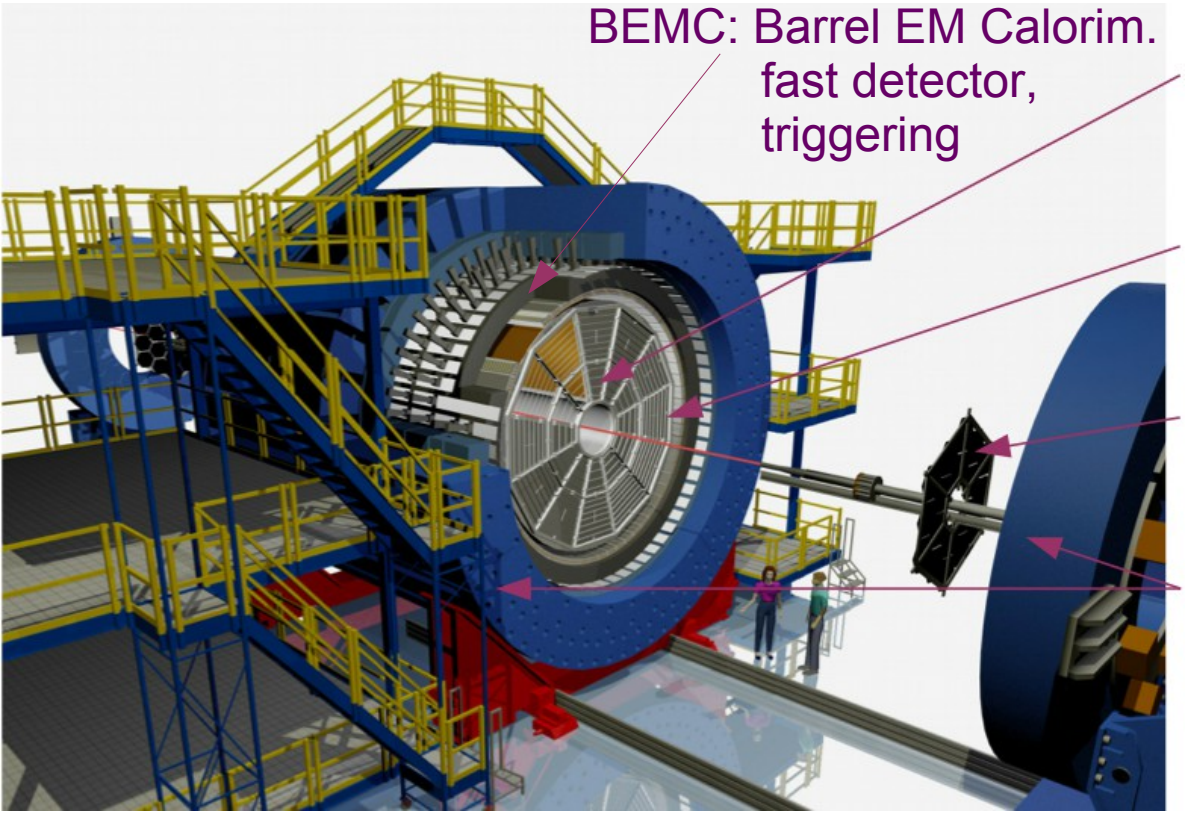
- Photoproduction on nucleus:
  - coherent, off whole nucleus, large R ↔ low p_T
  - incoherent, off individual nucleons, small R ↔ high p_T



elastic $\gamma + p \rightarrow J/\psi + p$

inelastic $\gamma + p \rightarrow J/\psi + p + X$ (nucleon dissociation)

The STAR detector, data selection



Trigger:

- J/ψ→ee: back-to-back showers in BEMC
  ρ→ππ: hits in TOF & ZDCs (Coulomb excitation)
- veto BBC: reject hadronic central collisions

Data sets

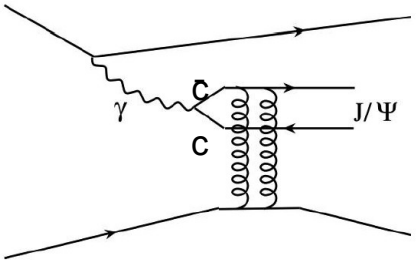
ρ: 2010 AuAu L = 1.1 nb^{-1}
J/ψ: 2015 p↑Au L = 140 nb^{-1}
2016 AuAu L = 12 nb^{-1}
2016 dAu L = 93 nb^{-1}

Offline selection:

- 2 tracks match BEMC showers or TOF hits, vertex in STAR center
- Tracks well reconstructed, dE/dx select ee or ππ, reject hadron pairs

UPC in Au+Au

<u>AuAu:</u> gluon content of Au



Models

<u>UPC photon flux:</u> from STARlight description

<u>STARlight:</u>
Comput.Phys.Commun. 212 (2017) 258
<u>Sartre:</u>
Comput.Phys.Commun. 185 (2014) 1835
Phys.Lett.B 803 (2020) 135277

<u>γAu</u>:

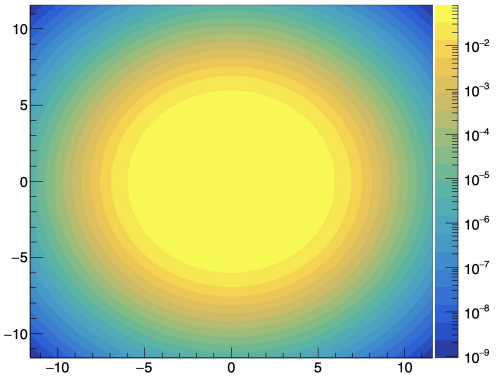
- STARlight:
  - γ+p→J/ψ+p from HERA data
    ⇒ γ+Au→J/ψ+Au classical Glauber, some gluon shadowing

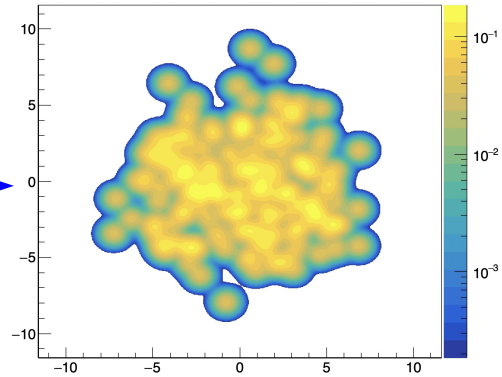
- Sartre, dipole model w/ saturation:
  - bSat dipole cross section
  - amplitudes *A* from ensemble nuclear configurations
  - Good-Walker:

$$\sigma_{tot} \propto \langle |A|^2 \rangle$$

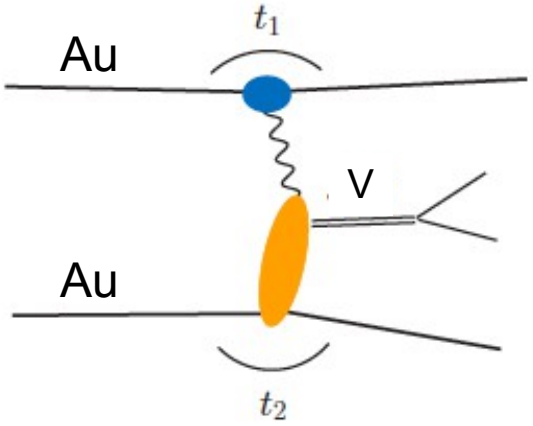
$$\sigma_{coh} \propto |\langle A \rangle|^2$$

$$\sigma_{inc} = \sigma_{tot} - \sigma_{coh} = \langle |A|^2 \rangle - |\langle A \rangle|^2 = \text{variance}(A)$$





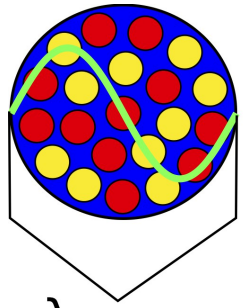
UPC processes in Au+Au

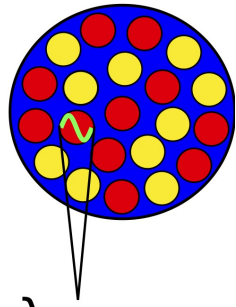


- Photoproduction vector meson V:
  - coherent, off nucleus, low p_T
  - incoherent, off nucleus, high p_T

  elastic $\gamma+p\rightarrow V+p$

  inelastic $\gamma+p\rightarrow V+p+X$ (nucleon dissociation)



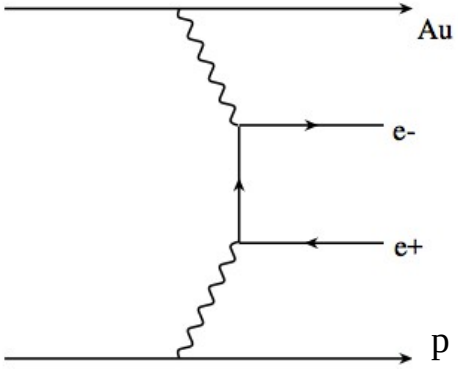


$J/\psi\rightarrow e^+ + e^-$

- QED 2γ (m_{ee} continuum):

  $\gamma+\gamma\rightarrow e^+ + e^-$

  (yesterday's topic, today's background)



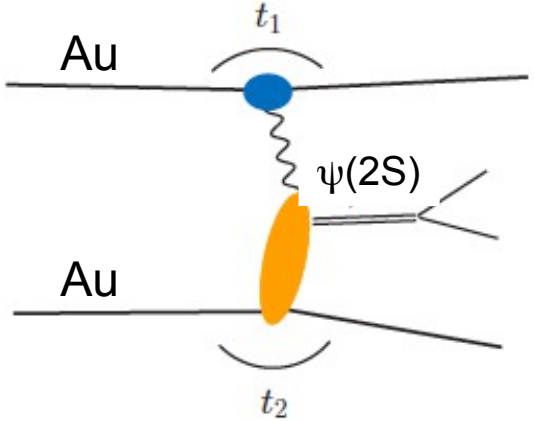
- Photoproduction $\psi(2S)$, decays:

  $\psi(2S)\rightarrow e^+ + e^-$ ($m_{ee}\sim m_{\psi(2S)}$)

  $\psi(2S)\rightarrow J/\psi+X$

  $J/\psi\rightarrow e^+ + e^-$ ($m_{ee}\sim m_{J/\psi}$) (feeddown)

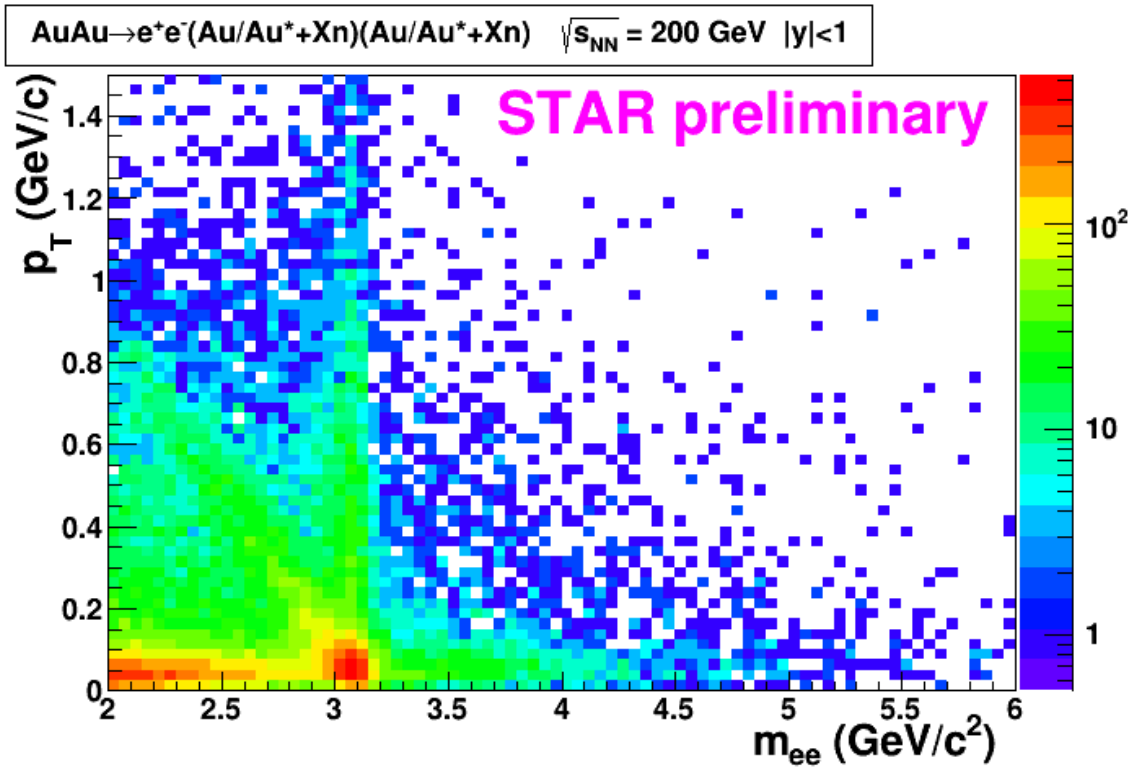
  Statistics sensitive to only $\psi(2S)$ coherent



Au+Au: data features

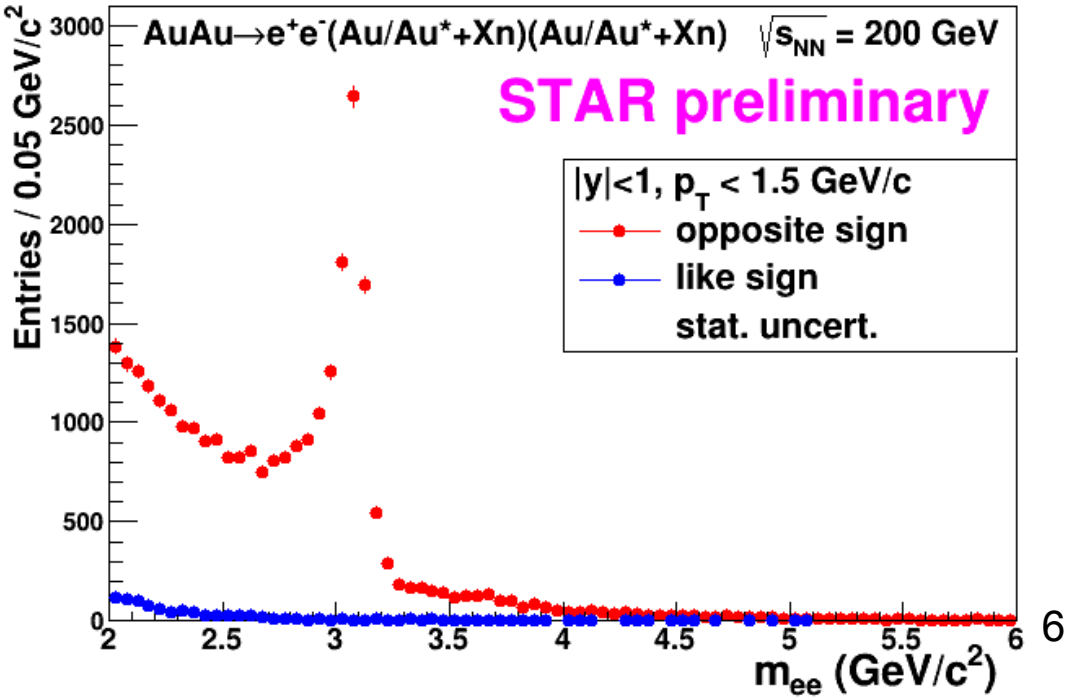
- p_T vs. m_{ee} for opp. sign pairs:

- High stat. features clear:
  - coherent J/ψ @ low p_T
    & rad. tail lower m_{ee}, higher p_T
  - incoherent J/ψ @ high p_T
  - QED 2γ continuum @ low p_T



- m_{ee} for opp./like-sign pairs:

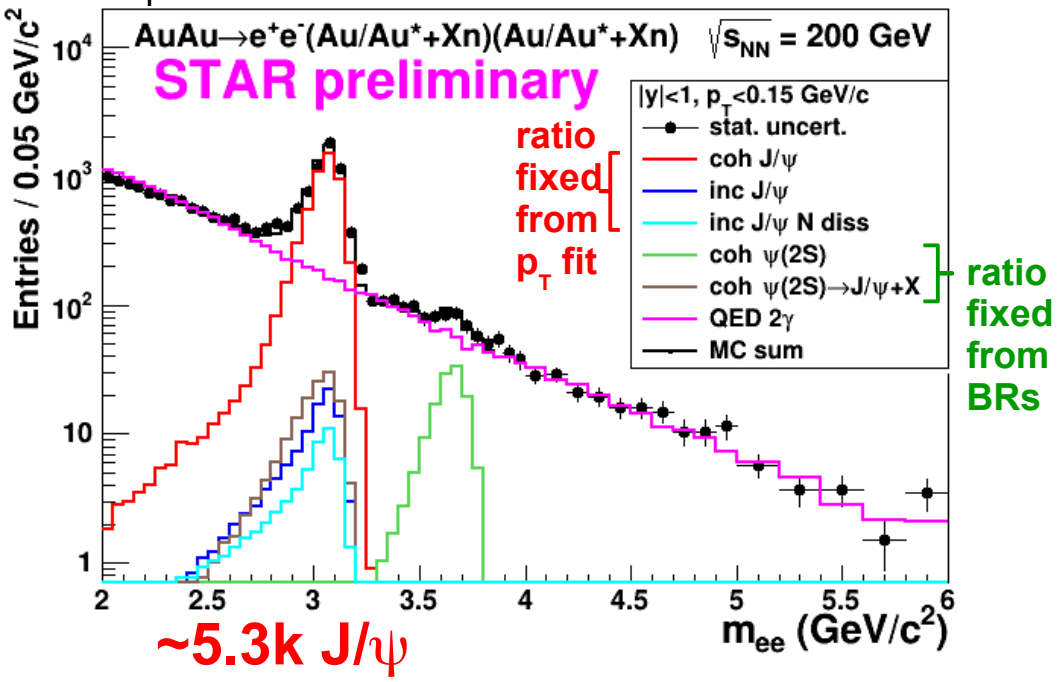
- Small like sign contamination,
  mostly @ low m_{ee}
- Take as combinatoric bkg.:
  final distributions =
  opposite sign - like sign



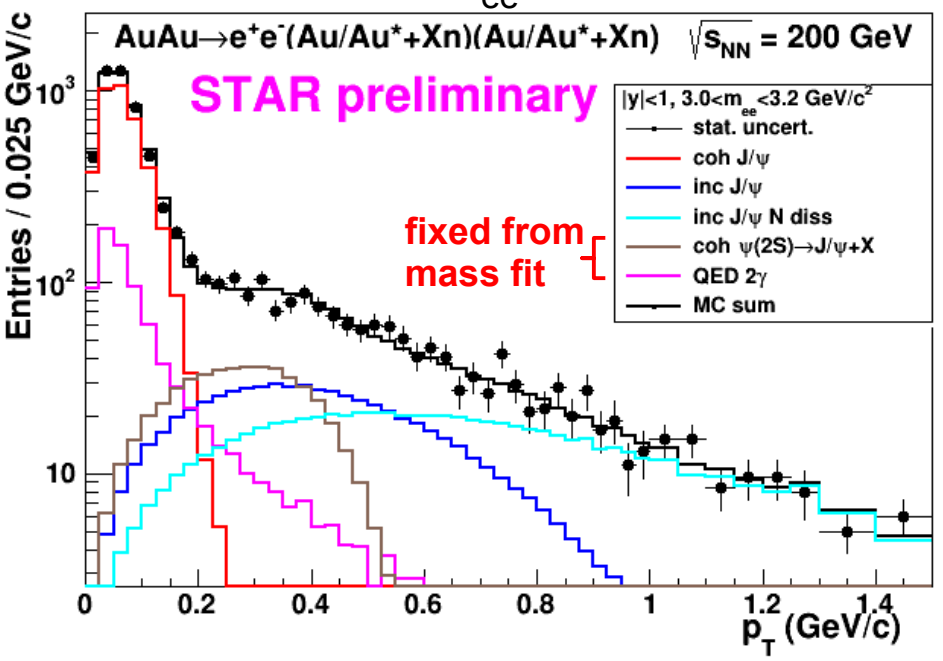
UPC procs→data comparison: m_{ee}

- UPC processes (slide 3) generated w/ STARlight, modifications:
  - p_T of coherent J/ψ & 2γ too high, reweighted to match data
  - incoherent J/ψ w/ nucleon dissociation p_T shape from HERA*
- processes → STAR simulation → templates; fit sum to data

- p_T < 0.15 GeV/c:



- J/ψ peak 3.0 < m_{ee} < 3.2 GeV/c^2:

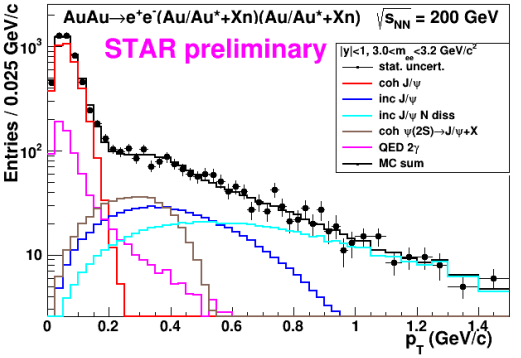


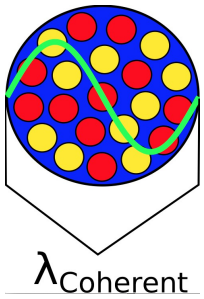
- Good description of data: VM peaks & rad. tails; 2γ shape ~3 orders mag. in σ
  J/ψ p_T coherent/incoherent components
- Use templates for: background subtractions, acceptance corrections

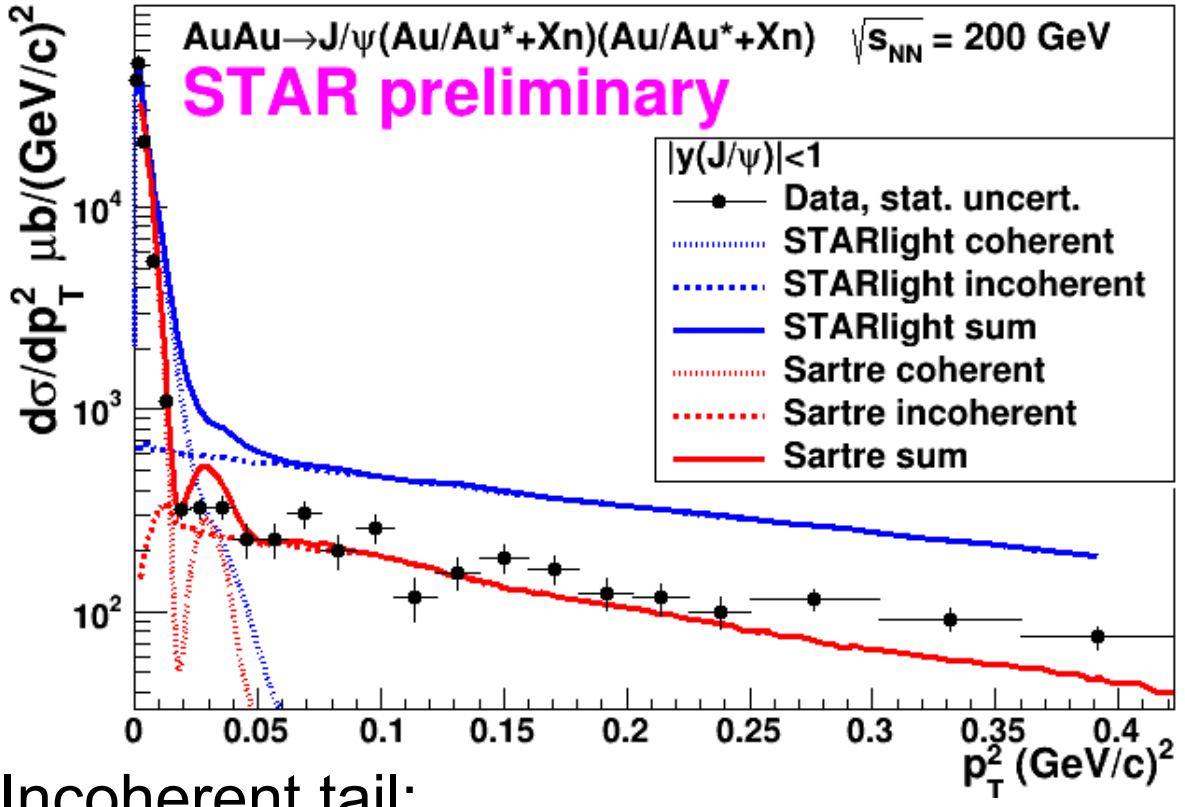
*H1 collab., Eur. Phys. J. C73 (2013) 2466

J/ψ p_T^2~|t| distribution

- Subtract non-direct J/ψ components (2γ , feeddown)
- Cross section: $d\sigma/dp_T^2$ (p_T^2~|t|)
- 2 components clear, data & models: coherent (low p_T^2) & incoherent (high p_T^2)







STARlight:
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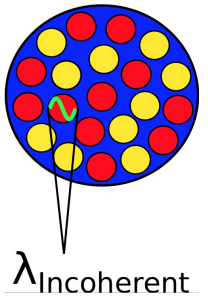


Incoherent tail:

- Data ~40% STARlight, simple model inadequate
- Sartre close in magnitude
- Highest p_T^2 data rise faster than models ↘

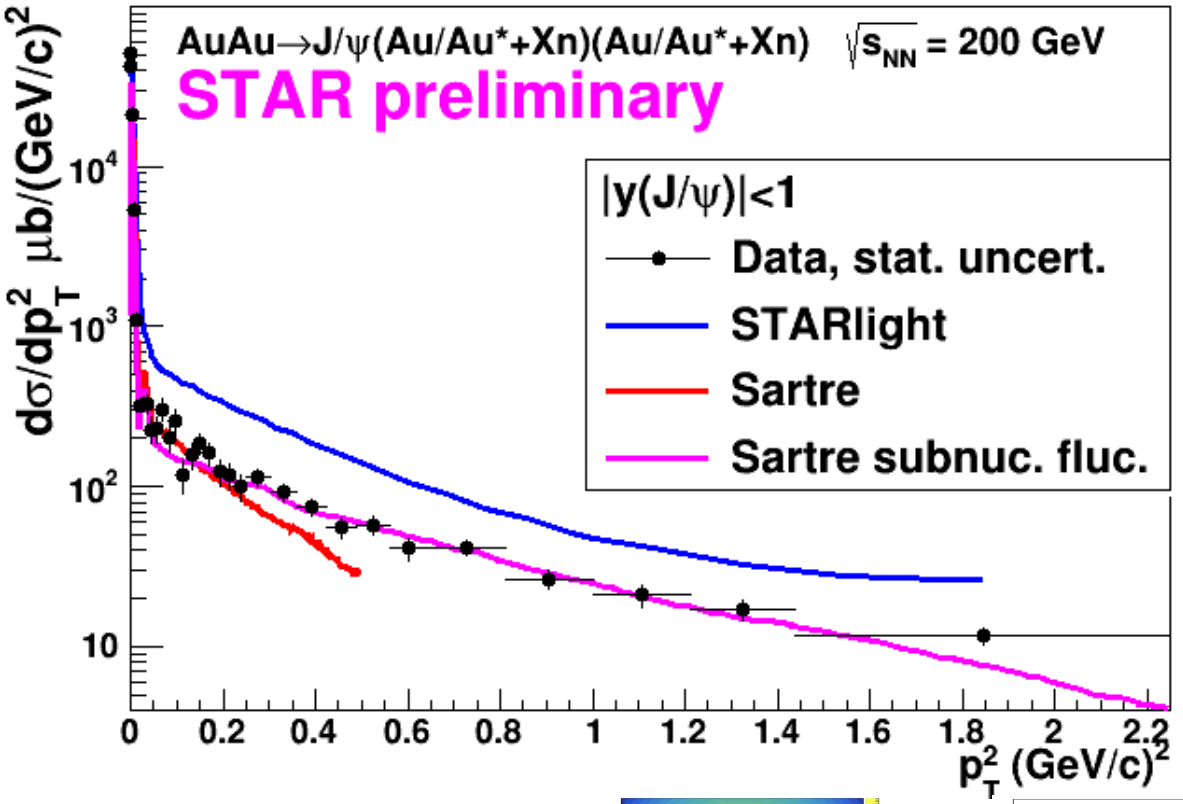
Incoherent J/ψ high p_T^2~|t| distribution

Empirical approach:

- STARlight elastic + H1 param.* inelastic (nucleon dissociation)

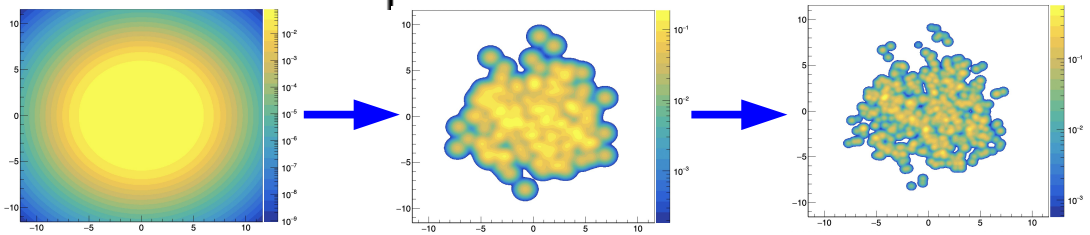
  $\exp(-4\cdot|t|)$ $(f_{inel}/f_{el})\cdot(1 + 0.45\cdot|t|)^{-3.58}$ *Eur. Phys. J. C73 (2013) 2466

- Good description shape → high p_T^2



Sartre model extension*:

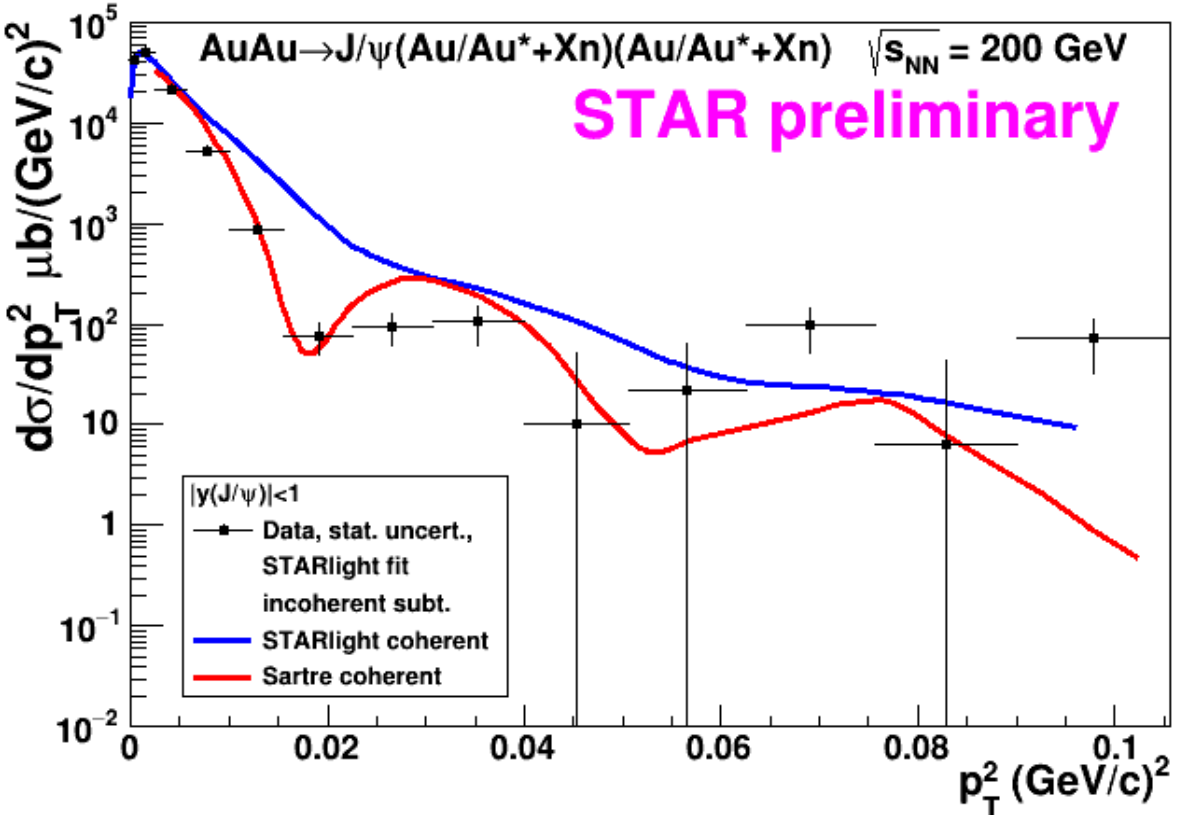
- Add subnucleonic fluctuations to nuclear configurations

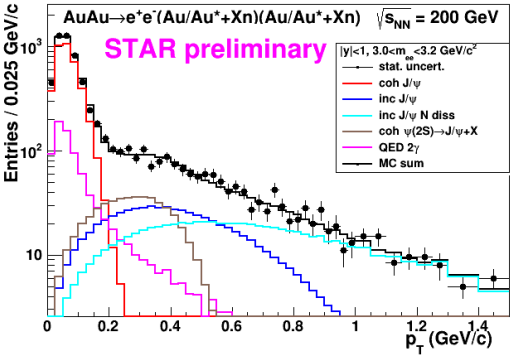


- Very good description magnitude, shape → high p_T^2 *T. Toll @ DIS 2021

Coherent J/ψ low p_T^2~|t| distribution

- Also subtract: STARlight incoherent fit to data





- dσ/dp$_T^2$~0 for p$_T^2$>0.1 (GeV/c)^2
- Total σ = ∫ dp$_T^2$

  data: 219 ± 5 (stat.) μb

  (scale uncert. ~10%)

  STARlight: 285 μb

  Sartre: 222 μb

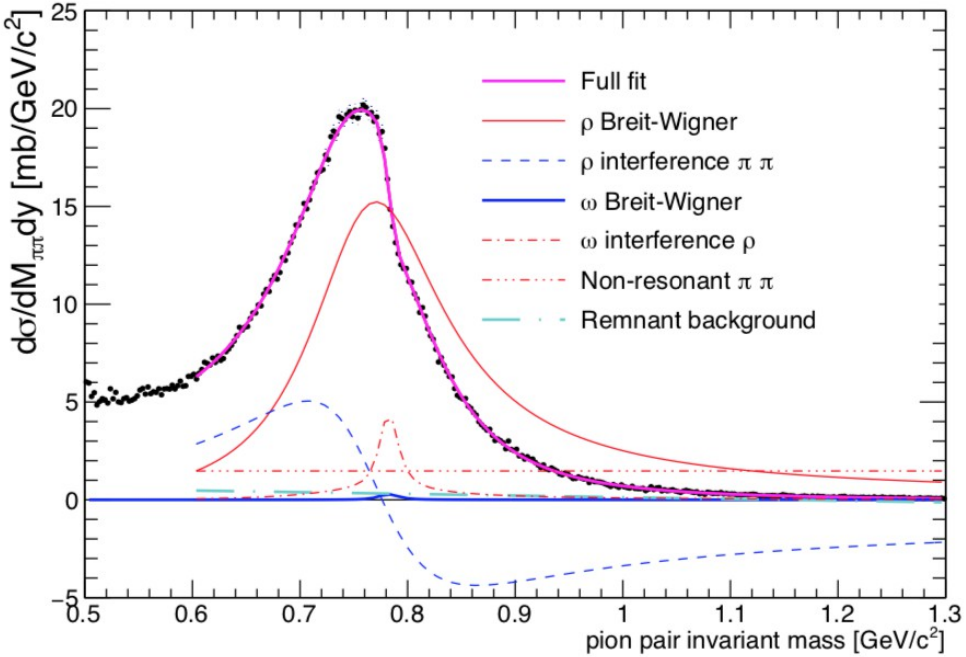
- Data/STARlight ~25%: shadowing; lowest p$_T^2$ data fall steeper
- Sartre: good description magnitude & shape @ lowest p$_T^2$
- Both models ~ data magnitude in higher p$_T^2$ tail
- Diffractive dips in Sartre → smeared by UPC γ p$_T$ in STARlight

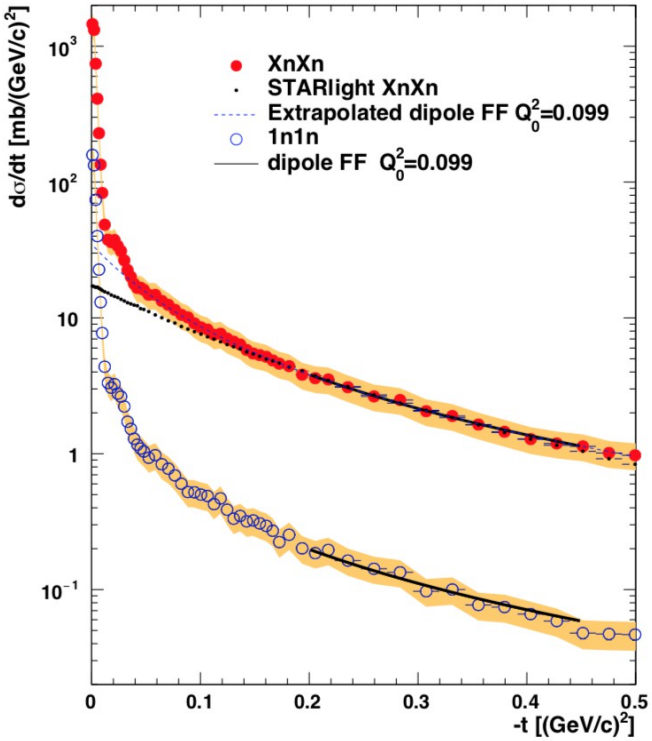
  data do not distinguish

UPC ρ in Au+Au

STAR collab., Phys. Rev. C 96 (2017) 54904

- UPC ρ photoproduction:
  - lose pQCD hard scale m_c w.r.t. J/ψ photoproduction
  - But: lower VM mass → much higher UPC cross section → statistics
  - can study diffractive structure in more detail

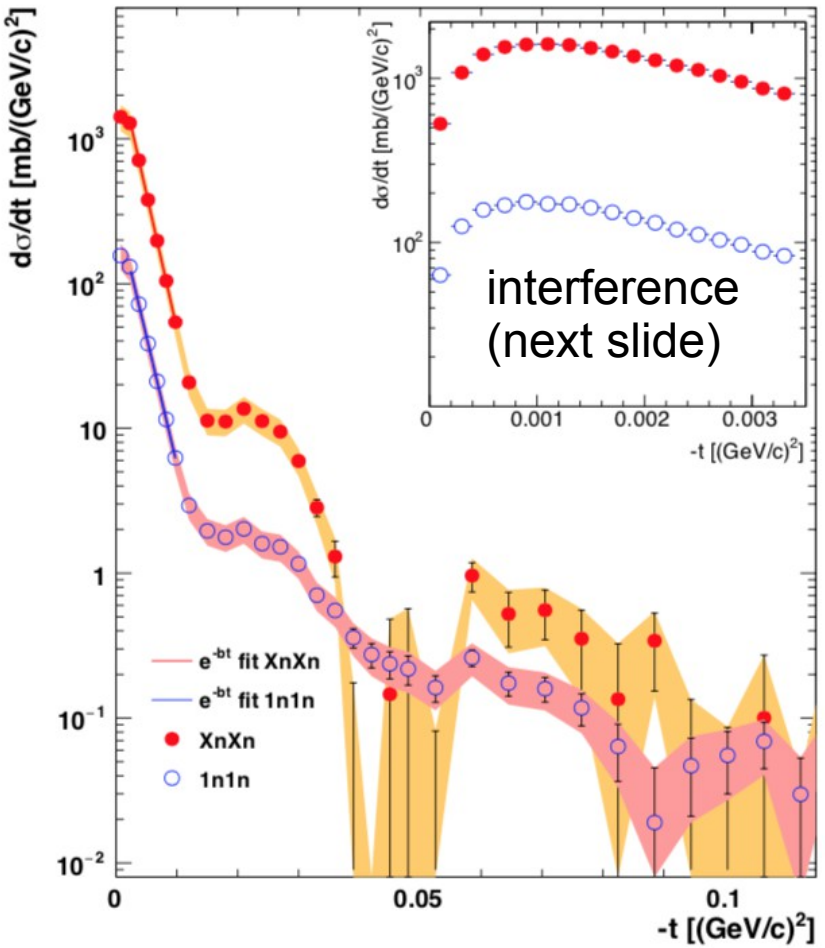




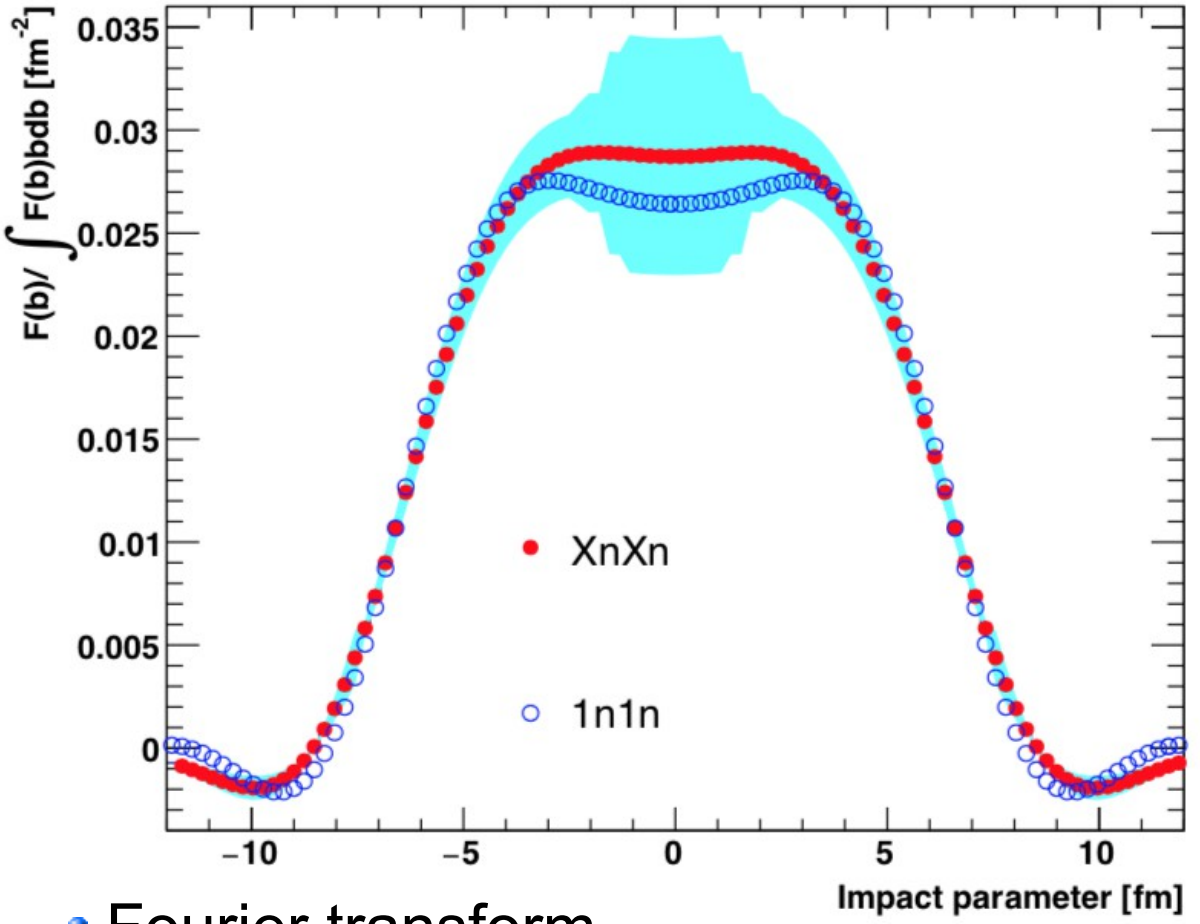
- Rich structure in m(ππ) spectrum:
  - ρ resonance
  - ω resonance
  - ππ continuum
  - interference between all

- ρ component |t| ~p_T^2 distribution:
  - coherent low |t|
  - incoherent high |t|
  - fit incoherent dipole form factor, subtract under coherent

UPC ρ in Au+Au



- Coherent |t| distribution, diffractive features clear:
  - 0th & 1st order peaks
  - 1st & 2nd order minima

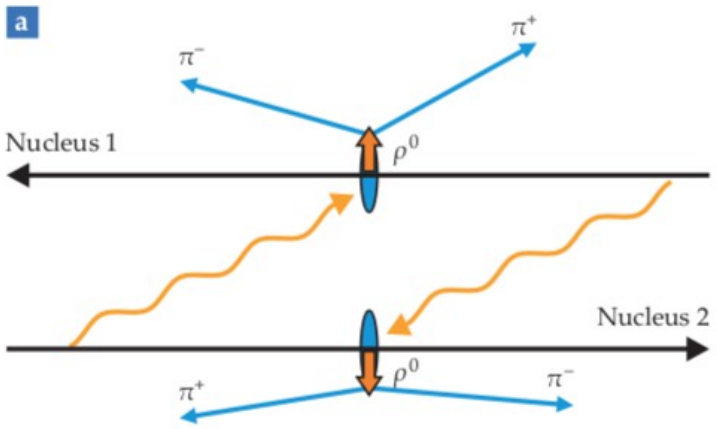


- Fourier transform
  |t| → impact parameter b:
  - uncertainty b~0 ↔ cutoff high |t|
  - sharp edges
  - negative high b ↔ destructive interference |t|~0

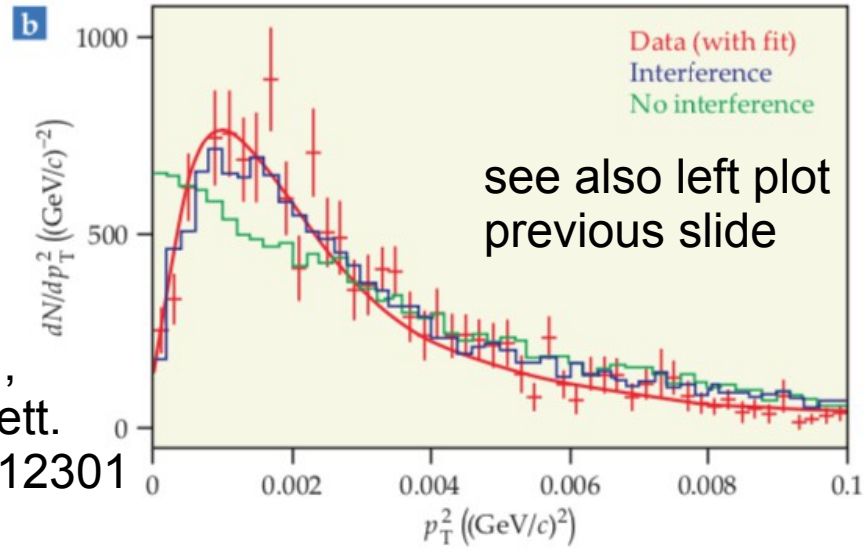
more UPC ρ: talk by Daniel Brandenburg

Lowest p_T^2~|t| distributions

- Interference: two sources γ emitter:



- Observed high stat. UPC ρ:

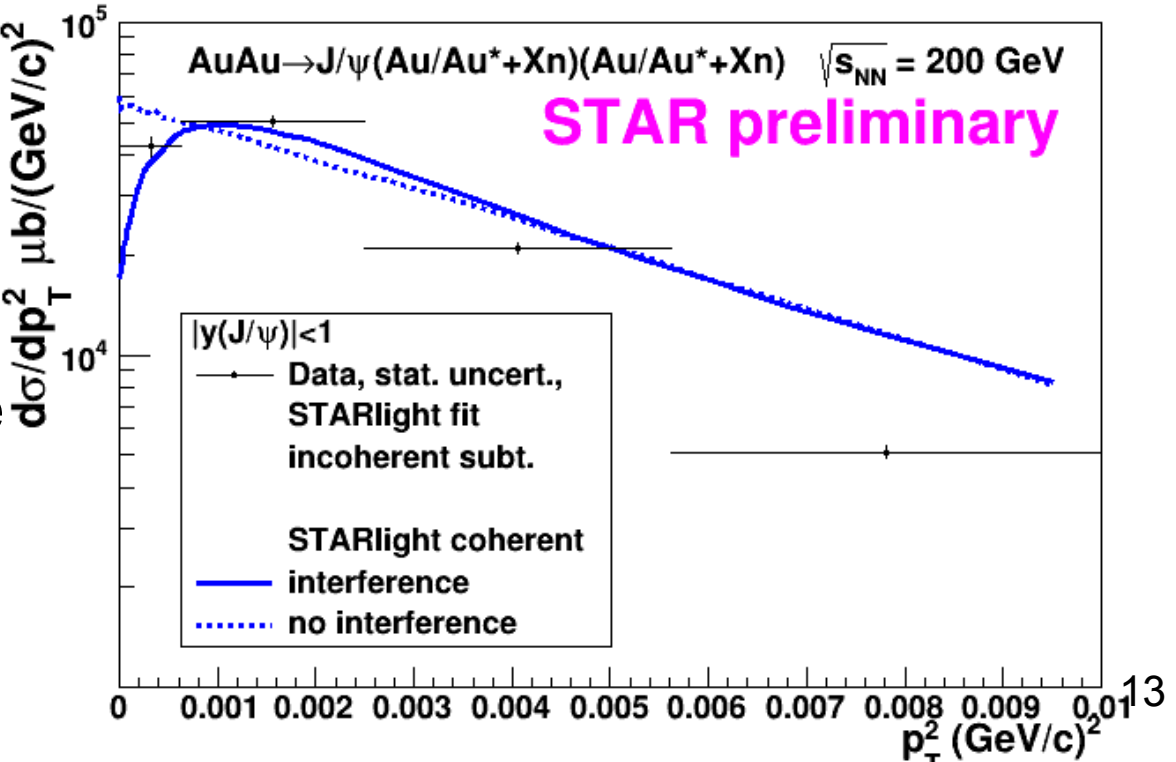


STAR collab., Phys. Rev. Lett. 102 (2009) 112301

- J/ψ: zoom lowest p_T^2

- Dip in lowest p_T^2 bin: consistent with interference

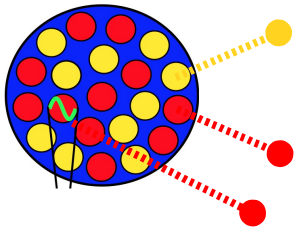
(bin size ~ p_T^2 resolution, precludes finer study)



Nuclear dissociation @ EIC

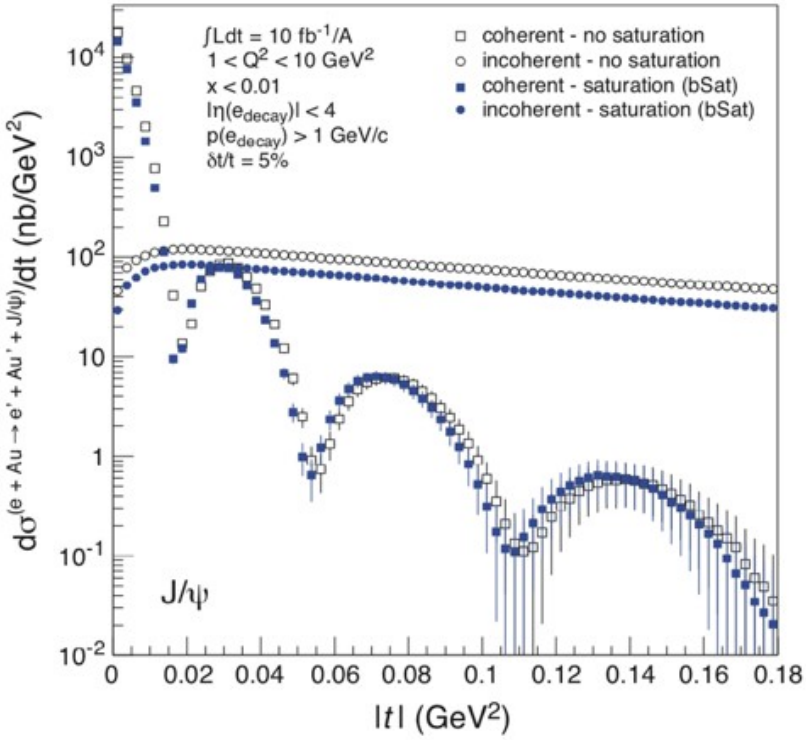
Significant program @ EIC:

- Nuclear imaging via coherent J/ψ |t|
- EIC statistics: several peaks/minima
- But: higher order features below orders of magnitude incoherent
- Incoherent scattering can breakup nucleus:

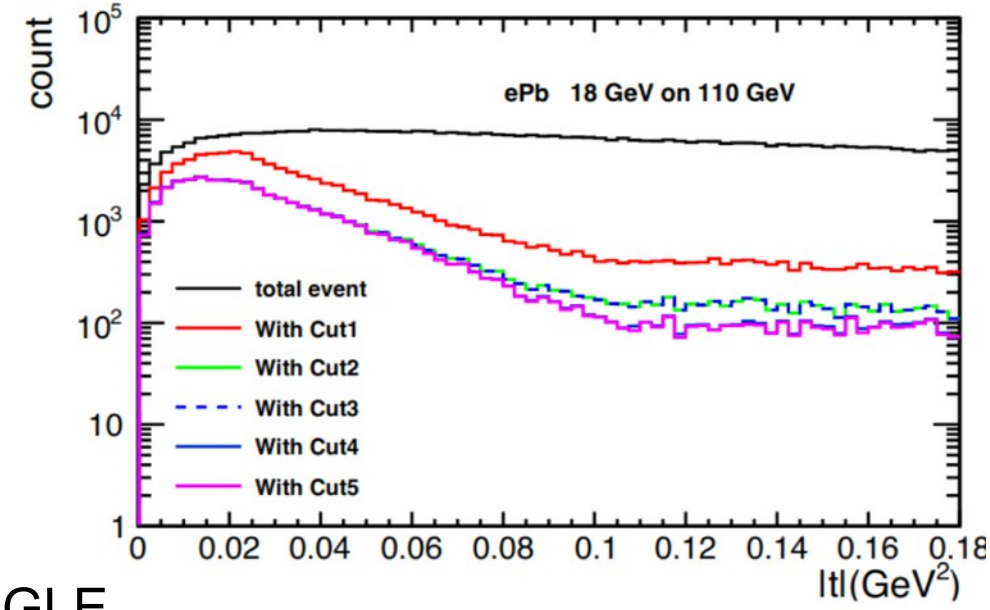


or leave an excited A*

- Either leaves low p_T p,n,γ may hit forward taggers



- BeAGLE†:
  - model of A,A* dissociation
  - model realistic taggers
  - here e.g. incoherent & levels of n,γ,p tag rejection

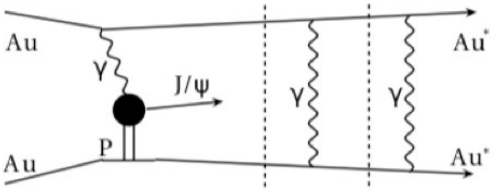


†https://wiki.bnl.gov/eic/index.php/BeAGLE

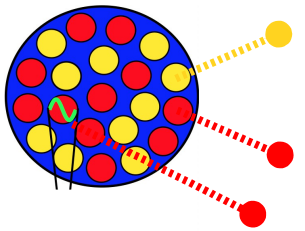
Nuclear dissociation UPCs ↔ J/ψ p_T

2 mechanisms nuclear dissociation in UPC

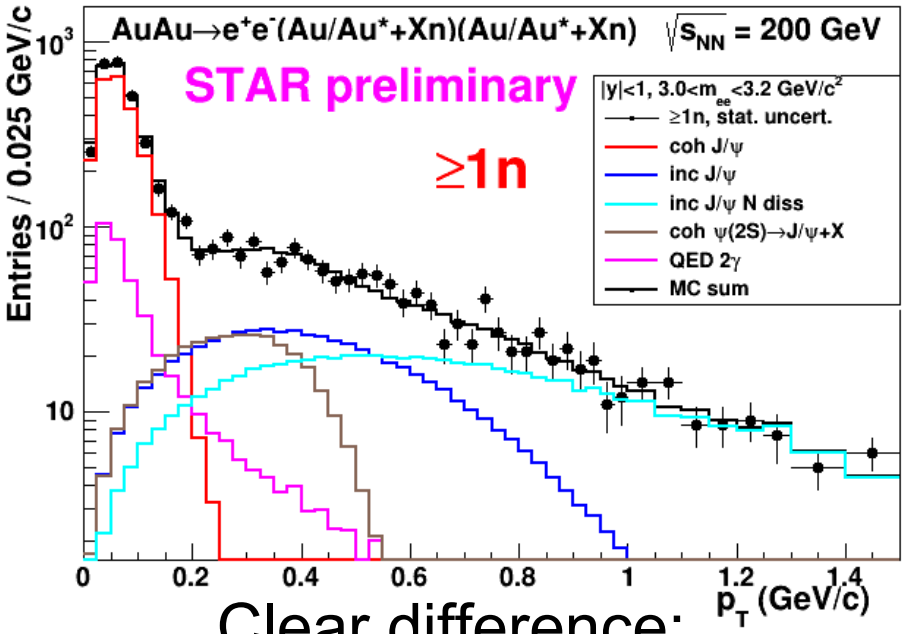
- Coulomb excitation: coherent & incoherent

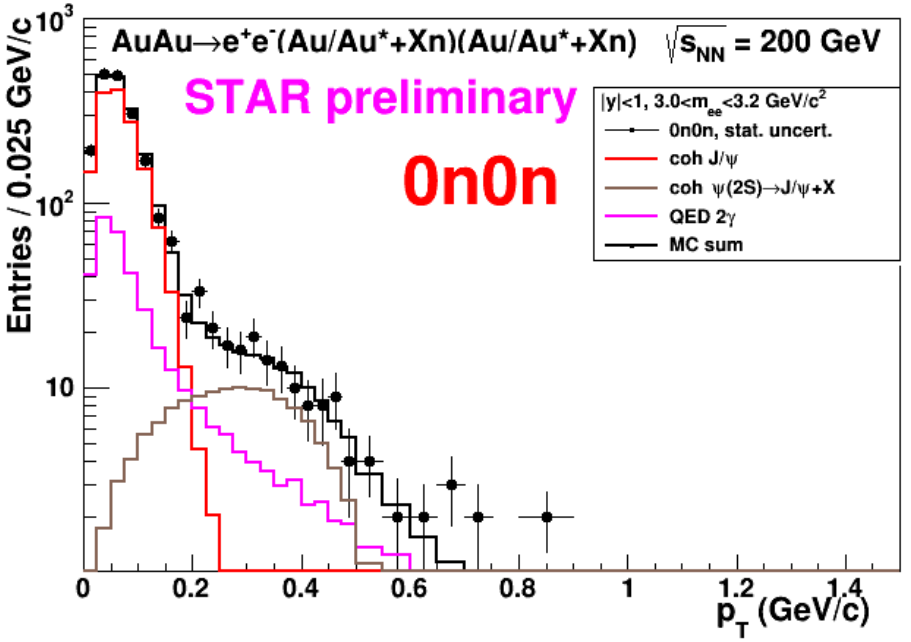


- Incoherent w/ breakup:



- ZDCs each side: tag ≥1 neutron with ~ nucleon beam energy (100 GeV)
- J/ψ p_T: at least 1 n either side vs. no neutrons either side (0n0n)





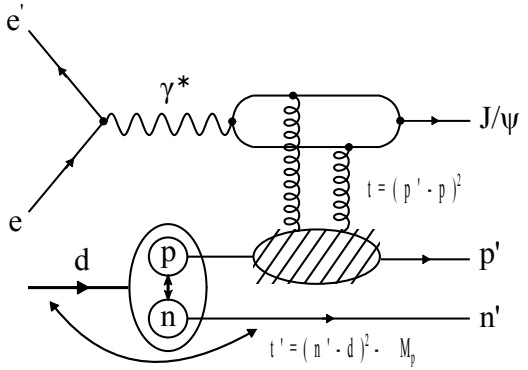
Clear difference:

- Low p_T coherent with & w/o neutrons
- High p_T incoherent usually produces neutron
- Relevant @ EIC: coherent/incoherent VM tagging compare models e.g. BeAGLE

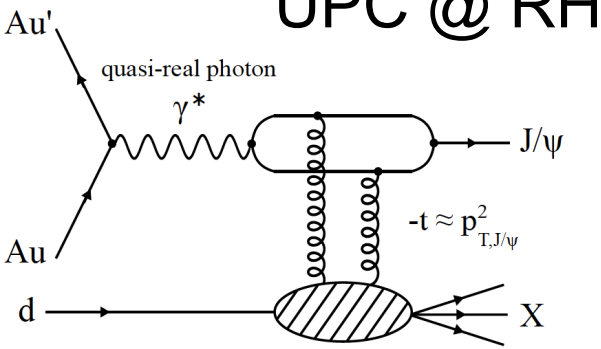
see talks by:
Wan Chang
Spencer Klein

UPC J/ψ in d+Au

- Deuteron is simplest nucleus, step 1 understanding nuclear effects
- Will study in detail @ EIC:



- Already have unique Q^2~0 data, UPC @ RHIC:



- Can test *d* wave functions e.g. AV18, Hulthen

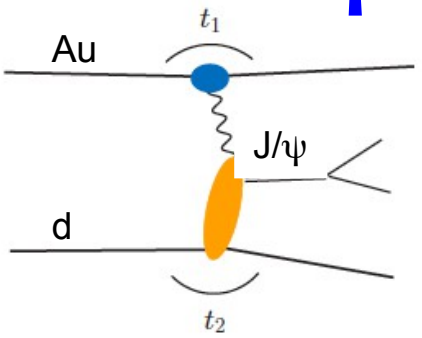
<u>As for AuAu:</u>

- J/ψ sensitive to *d* gluon content
- Dipole model w/ saturation, CGC
  - Coherent scattering
  - Incoherent scattering: subnucleonic (shape) fluctuations?

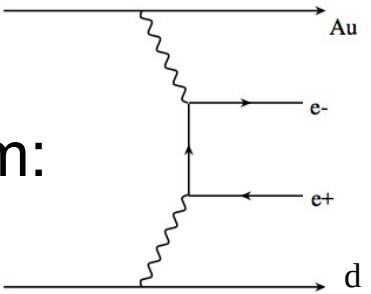
- Single neutron, clean breakup tagging

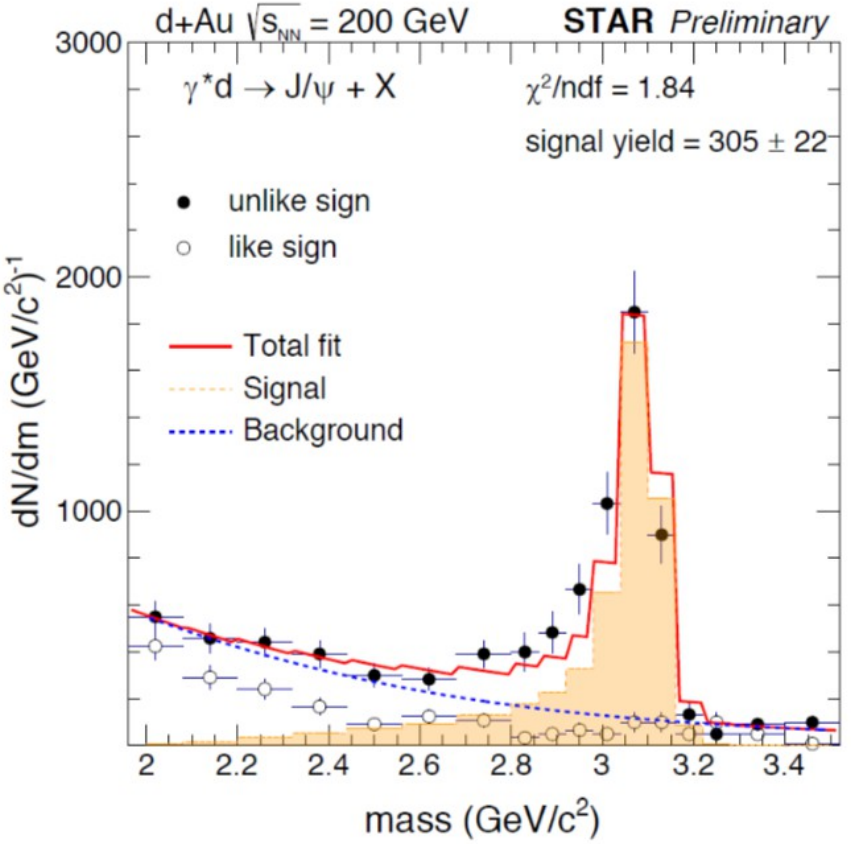
UPC J/ψ in d+Au

- Dominant process: high Au Z emits γ
  opposite d↔Au negligible



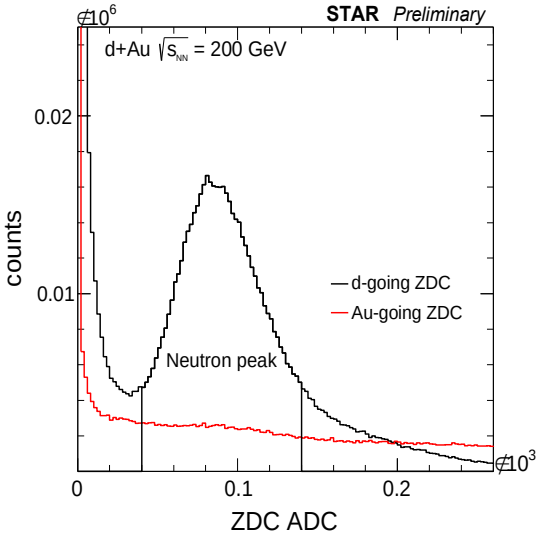
- And QED 2-γ e^+e^- continuum:





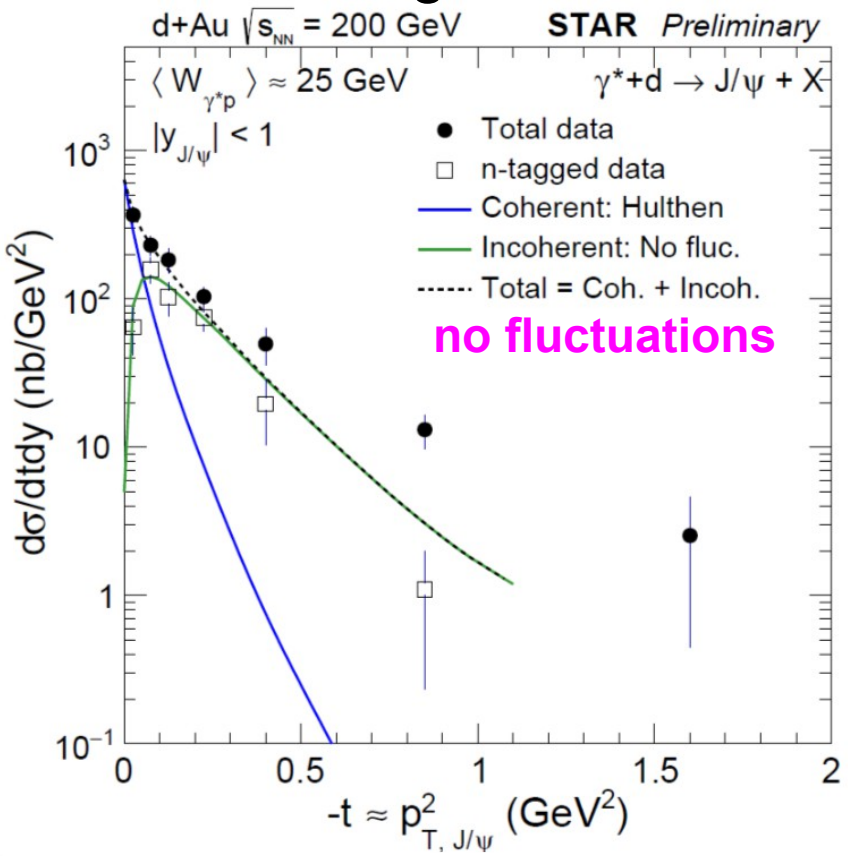
- Fit m_{ee} spectrum:
  - J/ψ template from simulation
  - analytic approx.: e^+e^- continuum + *hh* background
- Total J/ψ signal ~300 events
- Fit in p_T^2 bins → $d\sigma/dp_T^2$ ↘

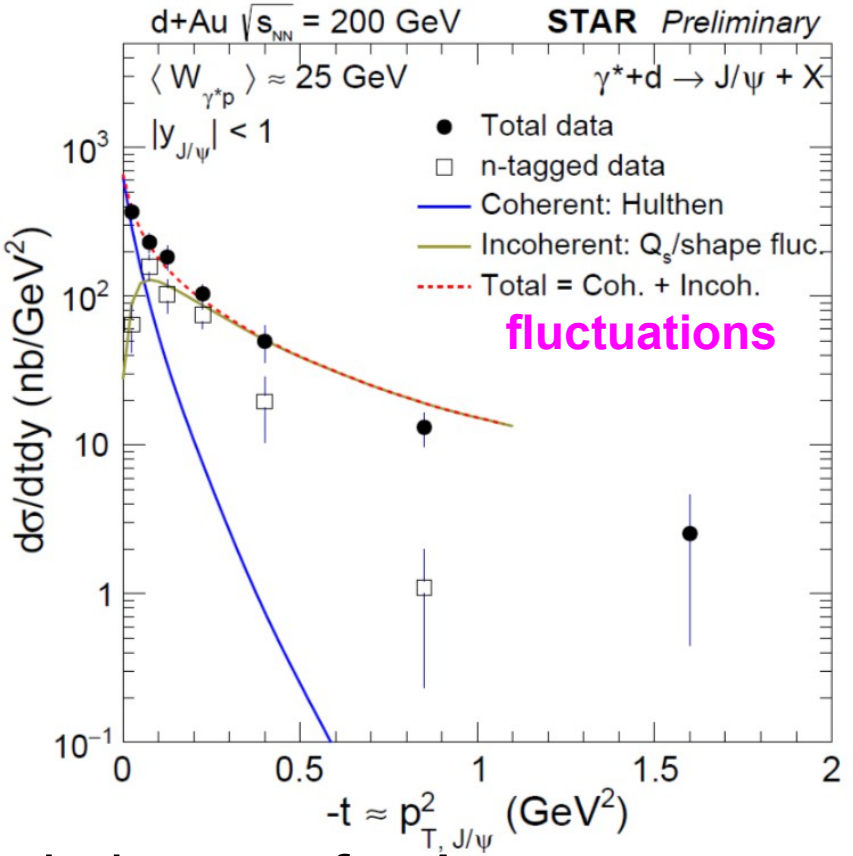
- Clean single-neutron tagging in ZDC:



UPC J/ψ p_T^2~|t| in d+Au

- Data don't distinguish w.f.'s AV18 vs. Hulthen; Hulthen shown here:

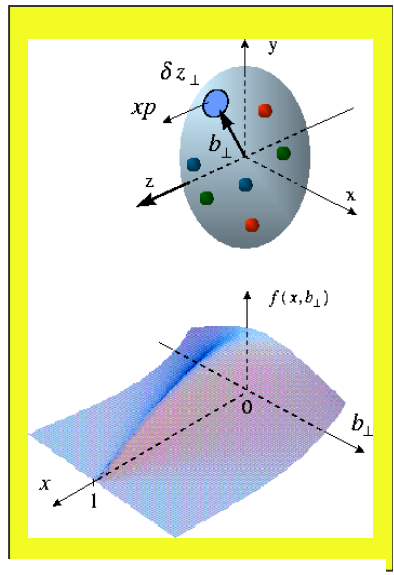




- Coherent/incoherent separation not as obvious as for Au:
  d not much larger than nucleon, p_T^2 dist. not so different
- Dipole model*: describe coherent/incoherent @ low p_T^2
  need fluctuations @ higher p_T^2 (like Au, Sartre ✓)
- n-tag: suppress coherent near p_T^2~0; lose tagger acceptance higher p_T^2

*H. Mäntysaari and B. Schenke, Phys.Rev.C 101 (2020) 1, 015203

UPC J/ψ in p↑+Au



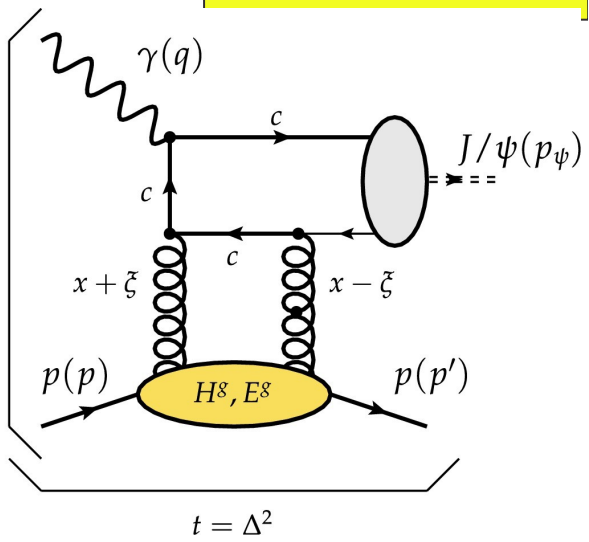
Generalized Parton Distributions:

- GPDs: Correlated quark momentum and helicity distributions in transverse space
- Access to: 3D imaging of proton
  q & g orbital angular momentum L_q & L_g
- GPDs for each q,g: $H^{q,g}/E^{q,g}(x,\xi,t)$ conserve/flip nucleon helicity
- The GPDs $E^{q,g}$ related to orbital angular momentum

Photoproduction w/ polarized protons

- Target particle transversely polarized proton p↑:
  J/ψ photoproduction $d\sigma/d\varphi \propto 1 + A_N^\gamma \cos(\varphi)$ $W = \sqrt{s_{\gamma p}}$

φ = azimuthal angle around beam axis



- A_N^γ calculable with GPDs*:

$$A_N^\gamma \propto p_T \cdot \frac{\mathrm{Im}(H^g \cdot E^{g*})}{|H^g|^2}$$

- $A_N^\gamma \propto E^g \Rightarrow$ sensitive to gluon orbital angular momentum L_g
- Unique RHIC capability: polarized protons, p↑Au run in 2015

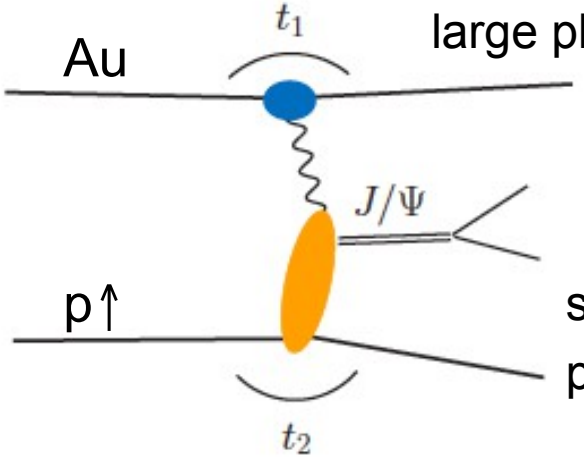
*J.P. Lansberg, L. Massacrier, L. Szymanowski, J. Wagner, Phys.Lett. B793 (2019) 33-40)

UPC processes in p↑+Au

$J/\psi \rightarrow e^+ + e^-$

$\gamma p\uparrow$ J/ψ photoproduction:

- Au photon source, p↑ target dominant process



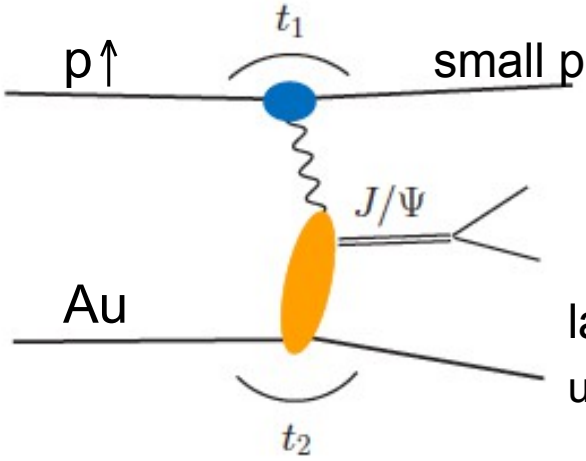
large photon flux $\propto Z_{Au}^2$

small nucleon target, high p_T

polarized target, $A_N^\gamma \propto E_g$

γAu J/ψ photoproduction:

- p↑ photon source, Au target



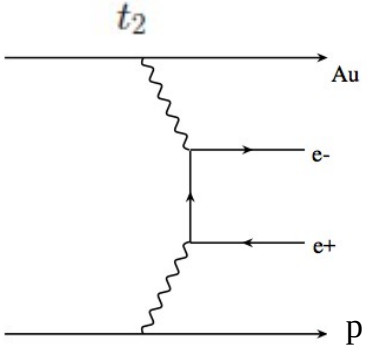
small photon flux $\propto Z_p^2=1$, small σ

large nuclear target, low p_T

unpolarized target, no asymmetry

Also:

- Continuum e^+e^- QED 2-γ process

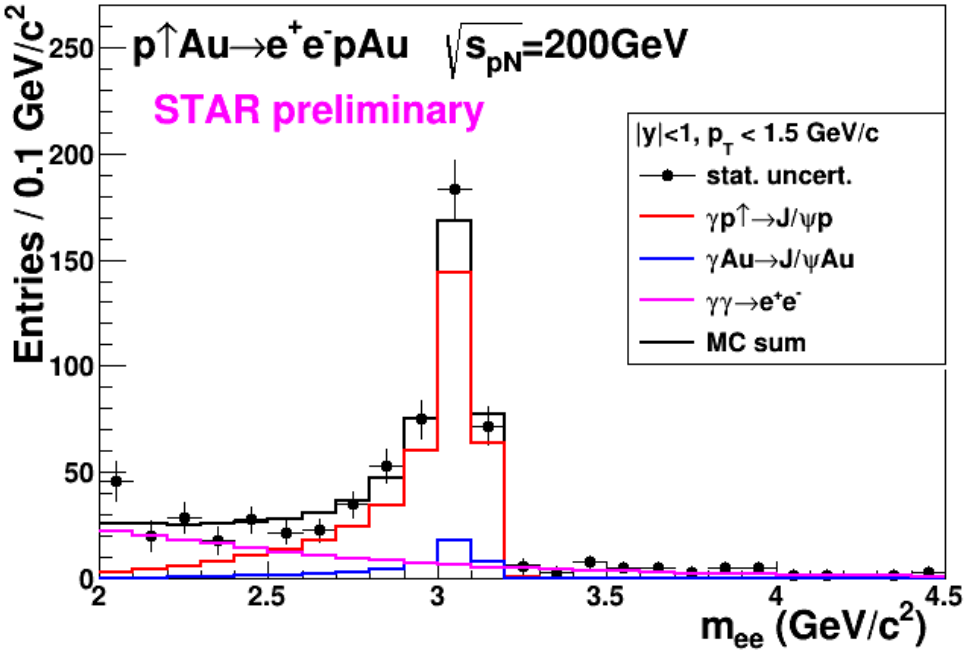


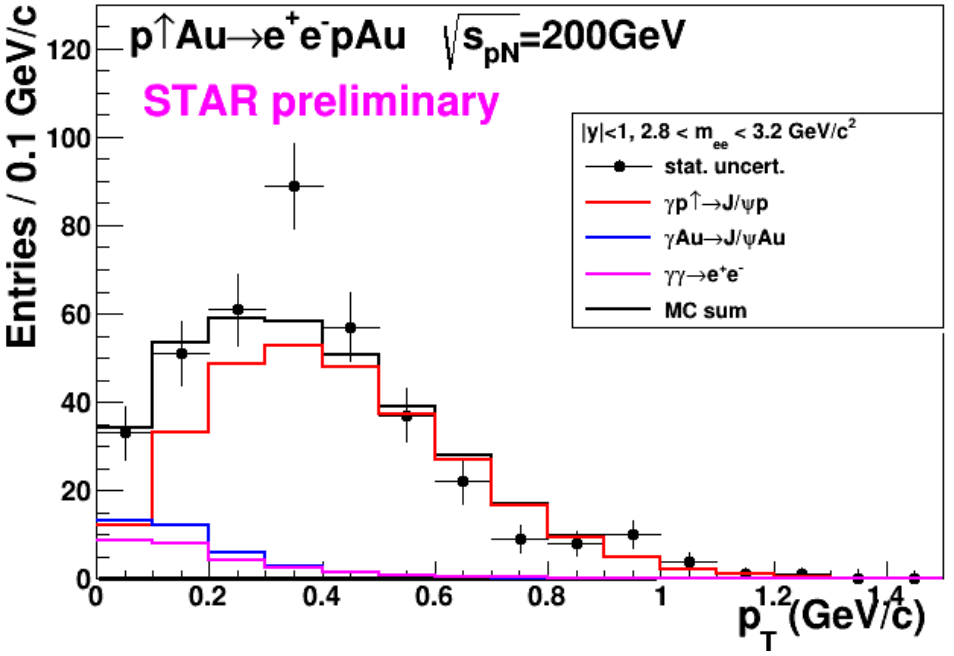
<u>ψ(2S) & inelastic incoherent processes seen in Au+Au:</u>

not discernible w/ statistics this data sample

UPC procs → p↑+Au data

- As for Au+Au fit sum MC templates to data:
- m_{ee}:
- p_T for $2.8 < m_{ee} < 3.2$ GeV/c²:





- Fit data to sum J/ψ (γp↑ & γAu) and QED 2γ
- m_{ee}: good description all features: J/ψ peak location, width & rad. tail
  QED 2γ continuum
- p_T: γp↑ @ high p_T ~ AuAu incoherent, γAu @ low p_T ~ AuAu coherent
- Want A_N^γ for γp↑ process; γAu & 2γ background @ low p_T, cut out
- For A_N^γ: $0.2 < p_T < 1.5$ GeV/c, purity = 92%

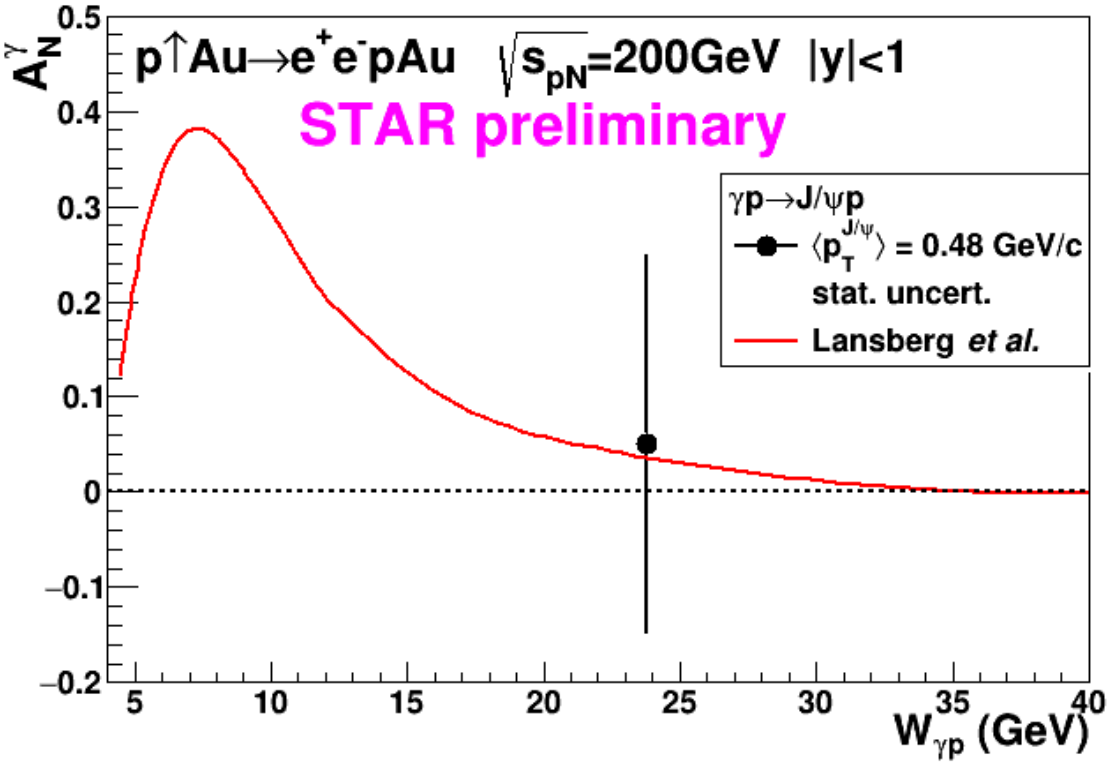
UPC J/ψ A_N^γ

- Signal range ($2.8<m_{ee}<3.2$ GeV/c^2, $0.2<p_T<1.5$ GeV/c), count events for: p↑ beam spin up/down, J/ψ cos(φ) >0 or <0 (total 231 events)
- Correct for: purity = 92%, p↑ beam polarization $\langle P \rangle$ = 61.3%
- Result:

  $A_N^\gamma = 0.05 \pm 0.20$ @ $\langle W_{\gamma p} \rangle = 23.8$ GeV, $\langle p_T \rangle = 0.48$ GeV/c

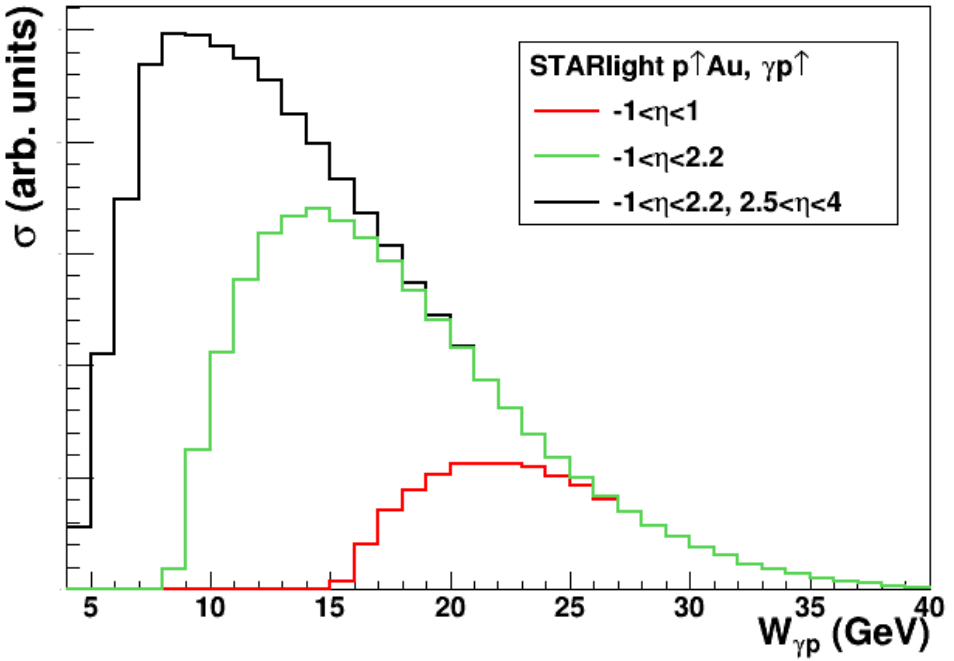
  $W_{\gamma p}$ = γp c.m. energy
- Null result, but proof of principle this measurement

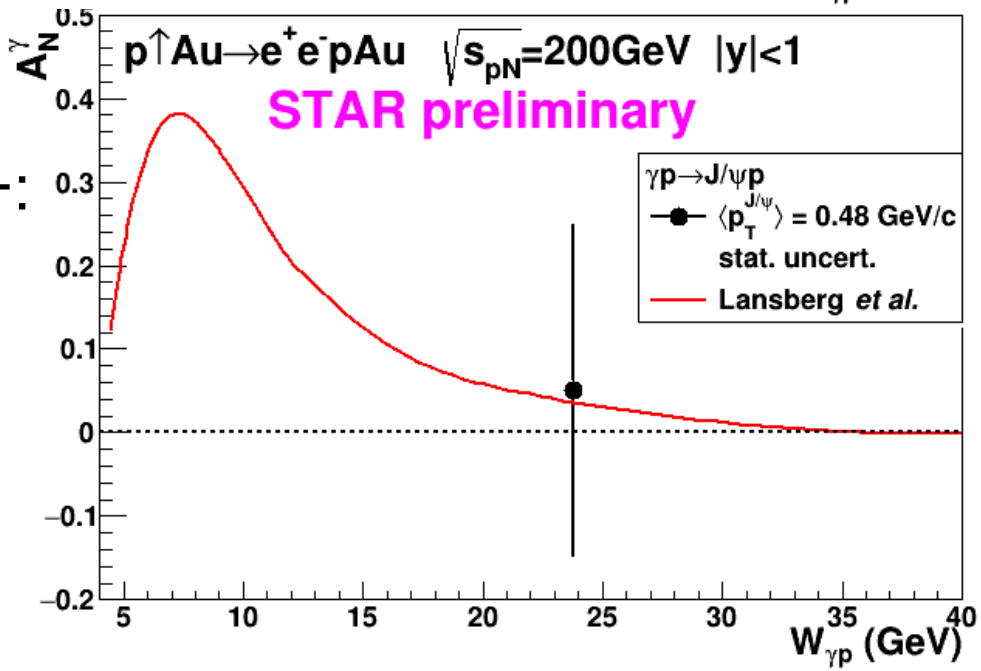
- Lansberg *et al.* have curve $\langle p_T \rangle = 0.7$ GeV/c, remade for 0.48 GeV:
  (J. Wagner, private communication)
- Can see what's needed to test such models:
  - higher statistics
  - lower $W_{\gamma p}$
- Future @ RHIC?



Future: UPC J/ψ A_N^γ

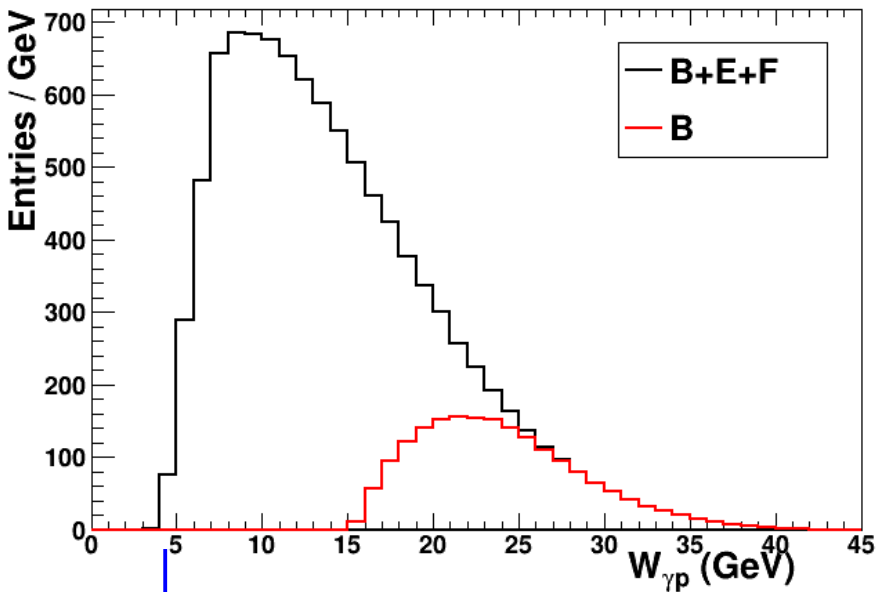
- Soon: 2017 √s=510 GeV p↑+p↑, analysis starting, but $W_{\gamma p}$~40 GeV
- These analyses used central STAR -1<η<1
- Already in STAR: iTPC tracking, endcap EMC triggering 1<η<2.2
- Coming soon 2021+ STAR Forward Upgrade w/ tracking & calorimetry 2.5<η<4
- Future RHIC p↑+Au runs 2022+: measure @ lower $W_{\gamma p}$
  - higher cross section (stats.)
  - larger A_N^γ
- Should be sensitive to e.g. Lansberg *et al.* models

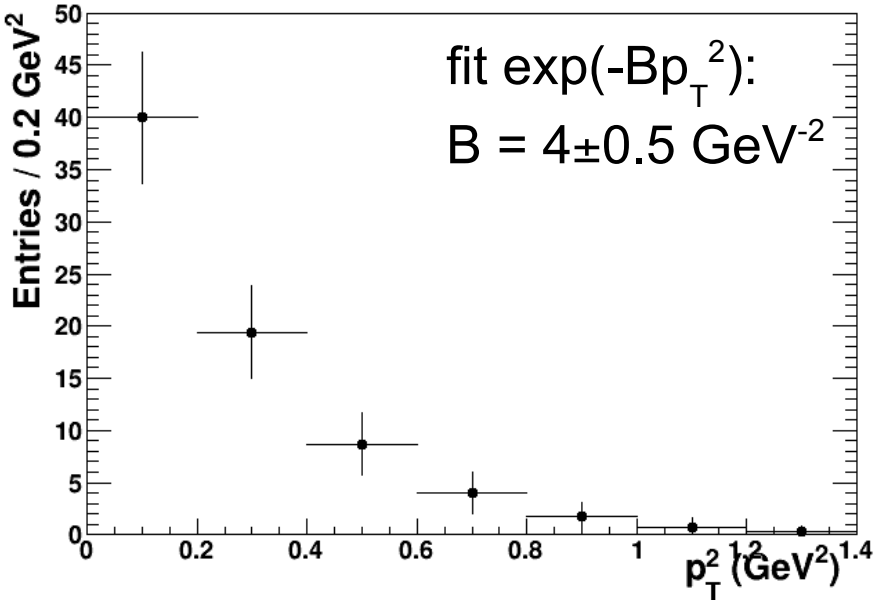


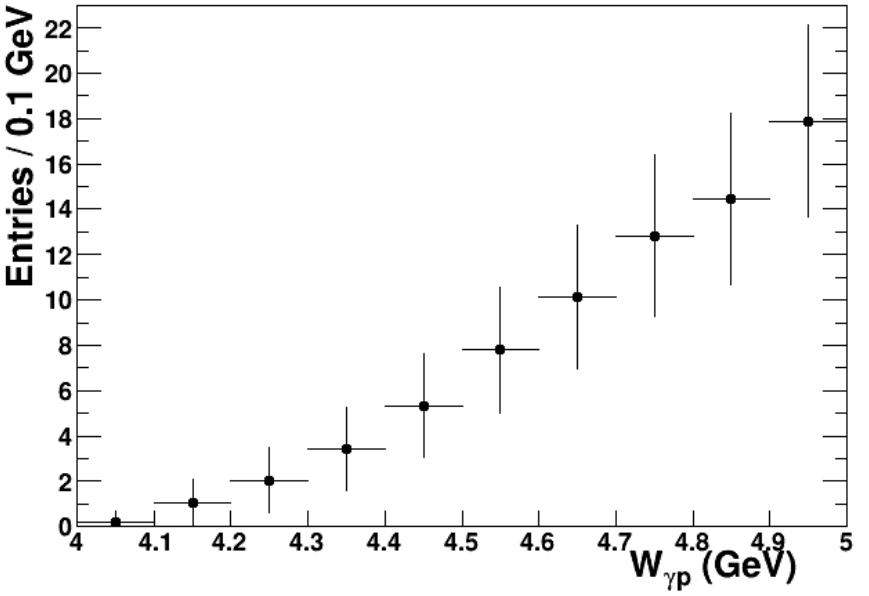


Future: UPC J/ψ ~ threshold

- Future 2024 run expected $W_{\gamma p}$ dist.:
- With Forward Upgrade acceptance down to J/ψ threshold ~4 GeV
- In threshold region $W_{\gamma p}$ < 5 GeV: only ~75 events
- Model sensitivity not clear, e.g. p_T^2 distribution:







Highlights & outlook: UPC VM @ RHIC

Highlights

- Clear 2 components coherent/incoherent: J/ψ in d,Au, ρ in Au
- Coherent component diffractive structure: ρ in Au
- High p_T^2 incoherent ⇒ subnucleonic fluctuations: J/ψ in d,Au
- Sartre, w/ subnuc. fluc. good description: J/ψ coh. & incoh. in Au
- Neutron tagging nuclear dissociation: J/ψ in d,Au
- Proof-of-principle asymmetry ∝ Eg: J/ψ in p↑

Outlook future RHIC runs*, STAR extended kinematic range

- Au+Au runs 2023 & 2025: 7× statistics
- p↑+Au run 2024: 9× statistics
- Also p↑+p↑ runs 2022, 2024: asymmetry measurement
- No future d+Au presently planned ☹,
  need to begin EIC construction! ☺

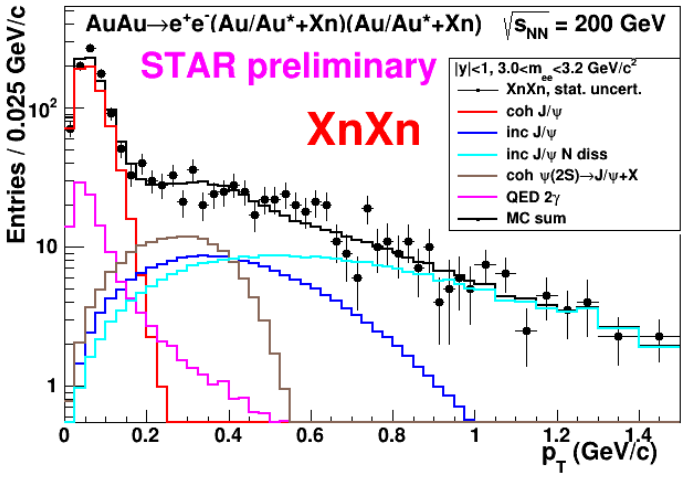
*"The STAR Beam Use Request for Run-21, Run-22 and data taking in 2023-25",
- The STAR experiment. https://drupal.star.bnl.gov/STAR/starnotes/public/sn0755

Extras

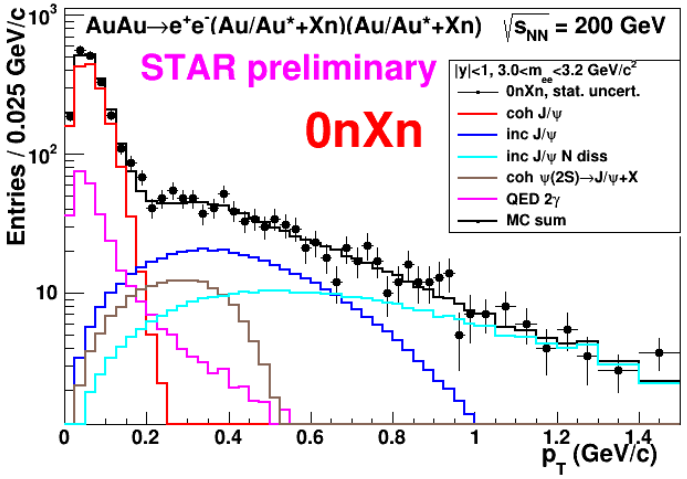
Au+Au: p_T for 3 ZDC categories

- Shown w/ vertical scale same range 10^3:

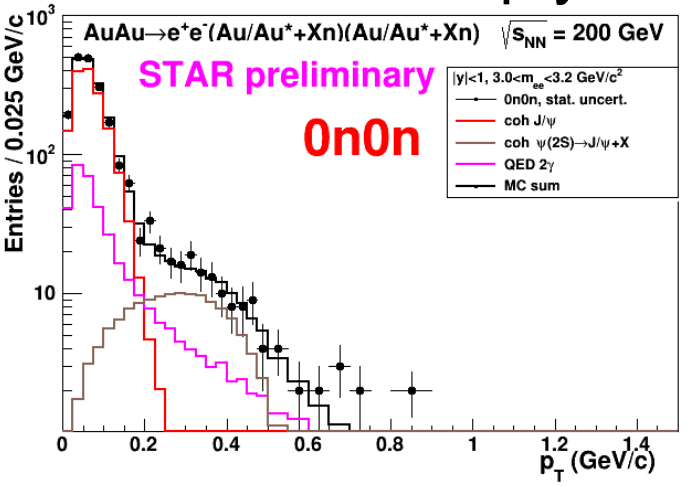
- ≥1n both ZDCs:



- ≥1n one ZDC, other ZDC empty:



- both ZDCs empty:



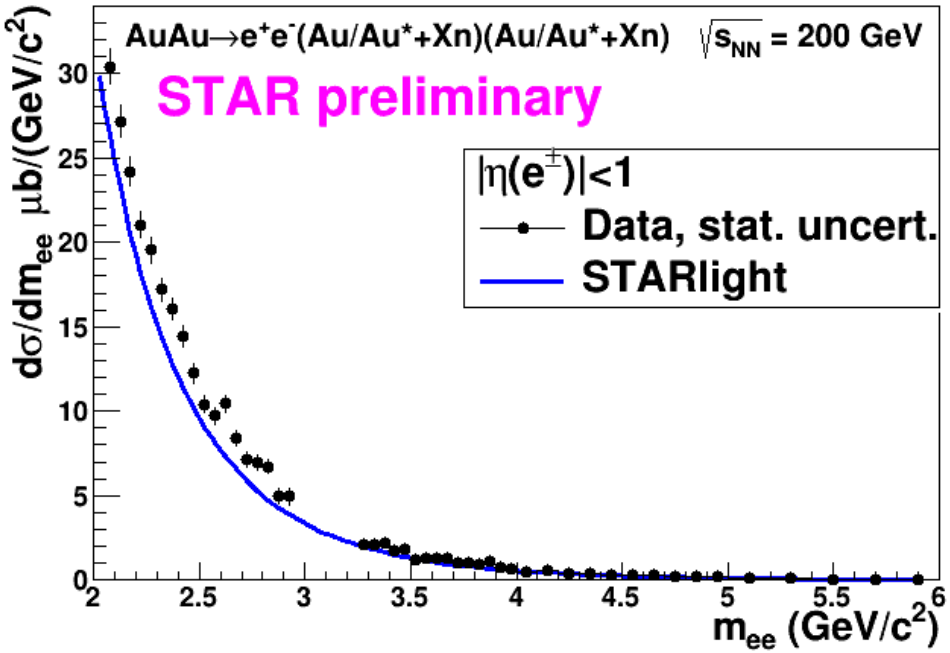
- Coherent peak always present & prominent regardless of neutrons: Coulomb dissociation
- Incoherent components only present when some neutrons → fit consistent with zero for 0n0n

$\gamma+\gamma \rightarrow e^+ + e^-$

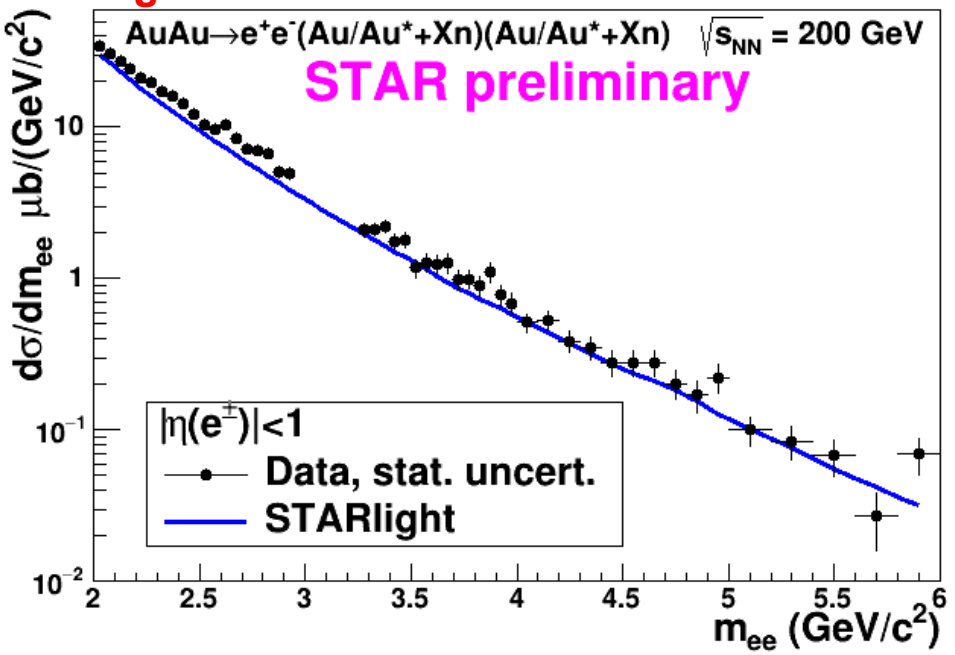
Free byproduct these data: $d\sigma/m_{ee}$ for $\gamma+\gamma \rightarrow e^+ + e^-$

- STARlight: describes shape over 3 orders magnitude in σ
- Data σ ~15% > STARlight:
- STARlight: no e^+e^- inside nucleus

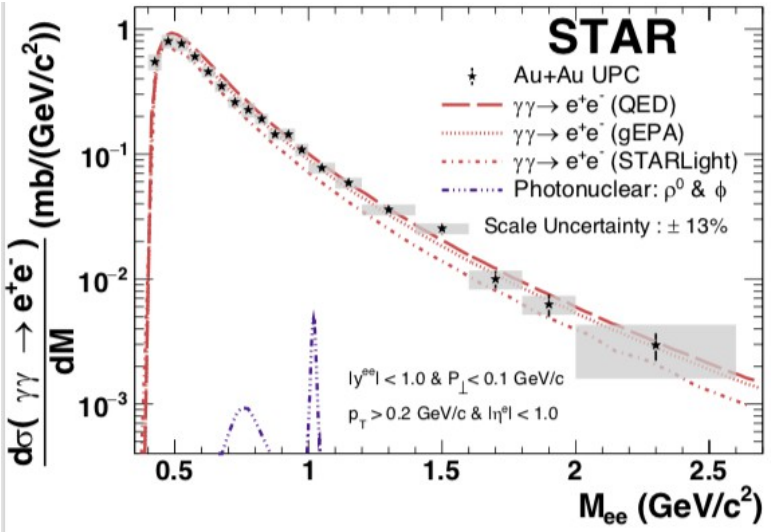
lin. scale



log scale

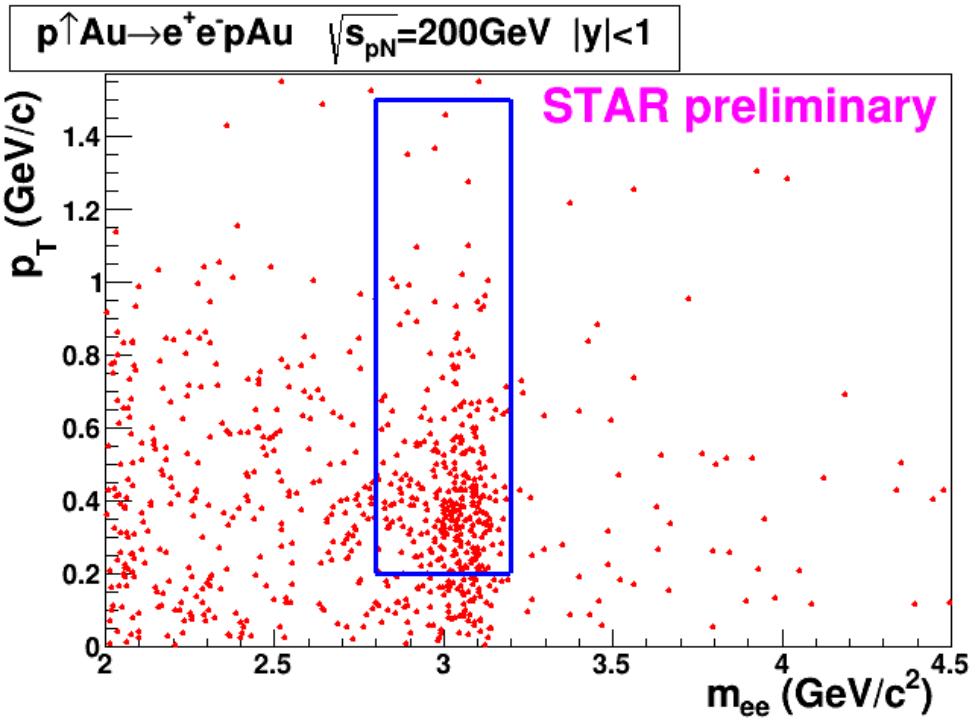


- Improved QED calculations agree better with data, here for lower m_{ee}:



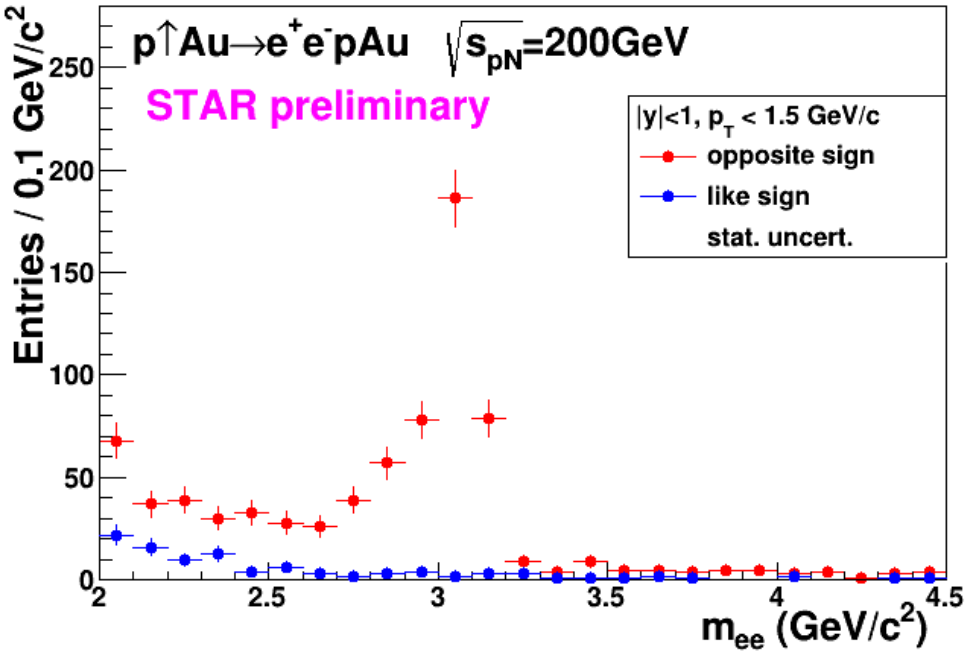
p↑+Au: p_T, m_{ee} distributions

- p_T vs m_{ee} for opp. sign pairs:



- Box shows fiducial region for A_N^{γ} measurement:
  $2.8<m_{ee}<3.2$ GeV/c^2,
  $0.2<p_T<1.5$ GeV/c

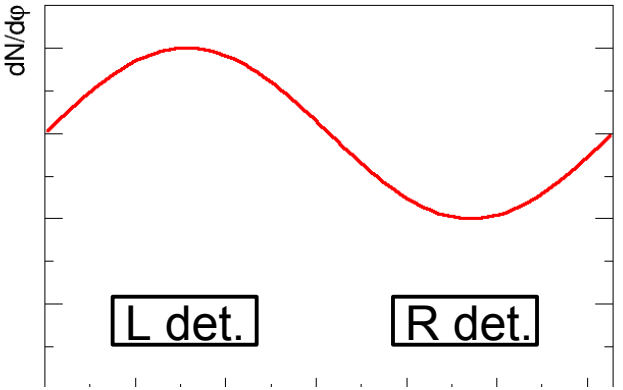
- m_{ee} dist. or opp./like sign pairs:



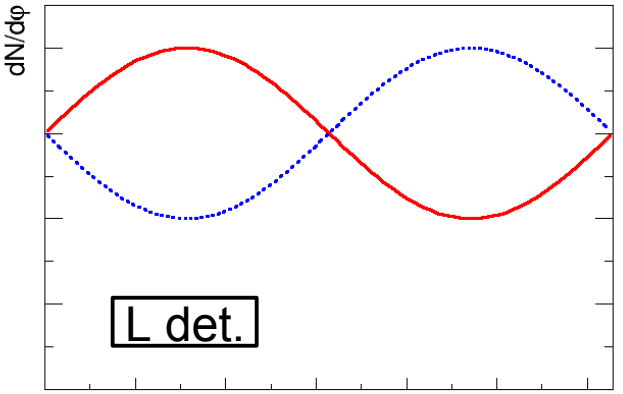
- For final distributions take (opposite-like) sign

Cross-ratio (for non-spin experts)

- If have one beam w/ spin up, and detectors left (L) and right (R) of beam, can measure asym. but would need to know relative acceptances of L/R detectors

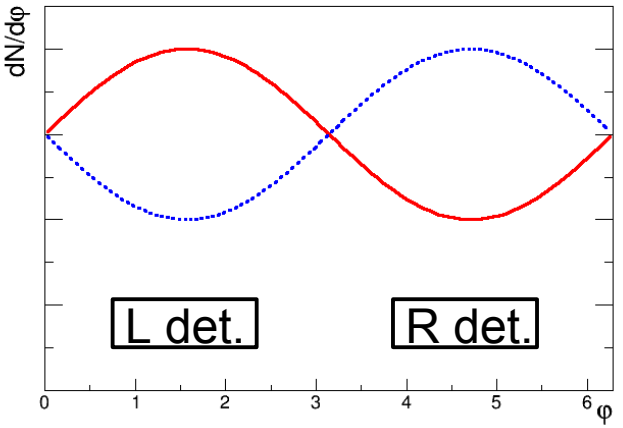


- If have one detector left of beam, and beam bunches w/ spin up (+) and down (-), can measure asym., but would need to know relative luminosities of +/- beams



- If have both L/R detectors and +/- bunches, acceptances and luminosities cancel out in the "cross-ratio"*:

$$\epsilon = \frac{\sqrt{N_{R+}N_{L-}} - \sqrt{N_{L+}N_{R-}}}{\sqrt{N_{R+}N_{L-}} + \sqrt{N_{L+}N_{R-}}}$$



*NIM 109 (1973) 41

*http://www4.rcf.bnl.gov/~cnipol/Documentations/Papers/TechniquesForMeasurementOfSpinHalfAndSpin1PolarizationAnalyzingTensors.pdf